FINAL REPORT

ON A

RADIOISOTOPE HEAT SOURCE
EVALUATION PROGRAM

15 May 1964 to 13 December 1964

Contract NAS 5-3849

by

COOK ELECTRIC COMPANY
TECH-CENTER DIVISION
MORTON GROVE, ILLINOIS

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
ADVANCED POWER SOURCES SECTION
GREENBELT, MARYLAND

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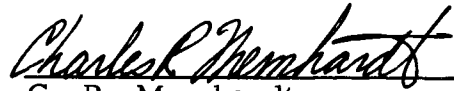# FINAL REPORT

TITLE: Radioisotope Heat Source Evaluation Program

CONTRACTOR: Tech-Center Division
              Cook Electric Company
              Morton Grove, Illinois
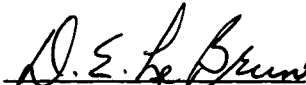
PERIOD: 15 May 1964 to 13 December 1964

CLIENT: National Aeronautics and Space Administration
              Goddard Space Flight Center
              Advanced Power Sources Section
              Greenbelt, Maryland
              Mr. Dale Harris, Technical Manager

CONTRACT: NAS 5-3849

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Project Engineer

APPROVED:

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 Instrumentation Section

ABSTRACT

12928

The primary objective of the radioisotope heat source evaluation program was the compilation of an annotated bibliography on the nuclear characteristics of the following isotopes: strontium-90, cesium-134, cesium-barium-137, promethium-147, polonium-210, plutonium-238, curium-242, and curium-244. A secondary objective of the program was the generation of a FORTRAN computer program capable of computing the low energy bremsstrahlung ($<$250 kev) emanated by candidate isotopic fuels. Promethium 147 was used as a typical radioisotope.

A total of 820 references were reviewed. Reference sources used were: Nuclear Science Abstracts 1948 - October 1964; National Academy of Sciences Nuclear Data Sheets; Reviews of Modern Physics Vol. 30, #2, pt II, April 1958; personal letters to authorities in the various fields; Battelle REIC Accession Lists 1960-1964.

At the beginning of each isotope section, the best values for the nuclear characteristics of that isotope are presented. These characteristics are: half life, spontaneous fission half life (when applicable), energy levels, decay schemes, spins, alphas/spontaneous fission (when applicable), and neutrons/spontaneous fission (when applicable).

The bremsstrahlung computer program was tested using promethium-147, oxide as a typical case. In addition to the program proper a flow diagram of the program is presented along with graphs of the generated bremsstrahlung spectrum.

author

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LIST OF ILLUSTRATIONS

1.0   INTRODUCTION

1.1   Purpose.   This final report has been prepared for the Advanced Power Sources Section, Goddard Space Flight Center, Greenbelt, Maryland in fulfillment of the requirements set forth in NASA Contract NAS 5-3849.

The subject program was initiated to satisfy two purposes. These were:

(1)   Assemble an annotated bibliography concerning the nuclear characteristics of a number of radioisotopes that are now being used, or are being contemplated for use, as radioisotope heat sources for satellite power supplies.

(2)   Develop a FORTRAN computer program capable of determining the intensity and average energy of the low energy bremsstrahlung emanating from some types of radioisotope heat sources.

1.2   Scope.   Annotated bibliographies have been prepared for eight radioisotopes.   These are:

(1)   Strontium-90
(2)   Cesium-134
(3)   Barium-Cesium-137
(4)   Promethium-147
(5)   Polonium-210
(6)   Plutonium-238
(7)   Curium-242
(8)   Curium-244

References chosen for inclusion in the bibliography have been restricted to those describing the nuclear characteristics of the isotopes.   Properties such as half lives, energy levels, decay schemes, energy per disintegration, etc., have been included. Properties such as uptake in humans, chemical preparation, metallurgy, distribution in fallout, etc., have been excluded.

A FORTRAN computer program was to be developed to aid in the determination of low energy bremsstrahlung spectra from beta emitting sources.   The FORTRAN program developed as a part of the over-all project effort was to be limited to the development of a

program from promethium-147 and promethium-147 oxide as illustrative cases.

1.3   General Program Background.   For some time it has been of interest to the Advanced Power Sources Section of NASA to make available to those persons investigating power production through isotopes an up-to-date annotated bibliography of those isotopes.   This particular bibliography was to be extended beyond the simple listing of articles and was to contain pertinent information on the isotopes described.

For example, if an article was concerned mainly with the energy levels of cesium-134, instead of listing only the energy levels, information such as the purity of the sample, its specific activity, the form of the sample, etc., would also be listed.   Also any apparent discrepancies between the listed values and other more commonly accepted values would be analyzed and commented upon.   It is to this end that the literature search and bibliography phase of the program has been directed.

(It should be noted here that the literature search has been confined solely to unclassified literature.   Although one classified document is referenced, none are described in detail.   It is recognized that this may limit to some degree the over-all completeness of the bibliography, notably for plutonium-238 and perhaps strontium-90.   However, it is felt that any necessity to classify the subject bibliography would severely limit its dissemination to interested individuals.)

The bremsstrahlung program was initiated because of the still highly elementary approach used, for the most part, in predicting bremsstrahlung below approximately 225 kev.   In many cases, it is the photon radiations of these energies that are most troublesome to the experimenter and satellite designer.   The FORTRAN program, as developed within the scope of the present program, was to be accomplished in two steps.   A review of the literature was to be made to determine first the empirical and theoretical basis for the emission of beta particles from promethium-147 as a typical case.   This portion of the study was to provide the beta spectrum that would constitute the input for the next step, the calculation of the generated bremsstrahlung.

The bremsstrahlung program has, as its ultimate objective, the development of recommendations for extending the computer sub-

routines and calculations to include the bremsstrahlung emanating from the more complicated compounds of promethium-147, other isotopes for power supply calculations, typical encapsulations and power supplies.

2.0 DESCRIPTION OF THE ANNOTATED BIBLIOGRAPHY

2.1 Reference Sources. The reference sources for the annotated bibliography were eight in number. These were:

(1) The Nuclear Science Abstracts, 1948 to 31 October 1964
(2) The National Academy of Sciences Nuclear Data Sheets
(3) The AEC document price lists
(4) Bibliographies at the conclusion of reference articles (Used mainly to search out articles published prior to the beginning of the Nuclear Science Abstracts, i.e., 1948)
(5) Review of Modern Physics, Vol. 30, Number 2, Part II, April 1958
(6) Battelle REIC Accession lists 1960-1964
(7) Personal letters to authorities in the various fields of endeavor
(8) Trips to scientific meetings and to other investigators as a result of searching the aforementioned sources

Approximately 825 references were reviewed from items a, b, c, and d. (The search through the REIC accession lists was discontinued because no applicable references were found back through 1960.)

Approximately 19 letters were written to various investigators in the radioisotopic field. Although the response to these inquiries was gratifying, it was found that most of the information received was to be found in the Nuclear Science Abstracts. In no case was any unpublished or "soon to be published" information received at that time. Therefore, for the most part, this line of investigation was abandoned. One scientific meeting was attended and one industrial firm was visited. On 18-19 May 1964 the "Proceedings of the Industry Meeting on Isotopic Power Development and Application" was attended at the Department of the Interior Auditorium in Washington, D.C. Also, on 16 September 1964 a visit was made to the Martin Company, Baltimore, Maryland. The two major topics of discussion during the latter meeting were:

(1)   The problem of the lack of references on the nuclear properties of strontium-90.

(2)   Experimental work being done at the Martin Company on external bremsstrahlung from promethium-147.   (This item will be discussed at greater length in section 4. 0.)

Personnel at the Martin Company were able to offer some assistance relative to the retrieval of only a few additional strontium-90 references.   However, the small number of references on the nuclear characteristics of strontium have been notable throughout the program.

2. 2   Reference Source Retrieval.   Because of the necessity of reviewing the articles chosen for inclusion in the annotated bibliography, institutions having these articles on file had to be located.   In all, four article retrieval sources were used.   These were:

(1)   The John Crerar Technological Library, Chicago, Illinois
(2)   The Northwestern University Technological Library, Evanston, Illinois
(3)   The Argonne National Laboratory Library, Lemont, Illinois
(4)   Office Technical Services (OTS) Washington, D. C. , Foreign Government Documentation Agencies

2. 3   Bibliography Format.   The eight radioisotopes studied are arranged somewhat arbitrarily in order of ascending Z.   At the beginning of each section the best available information is given relative to that isotope's nuclear characteristics.   Immediately after the quoted value, the reference cited is given.

Articles and reports within each section are arranged in chronological order beginning with the most recent.   In some instances where only the abstract of an article is presented, or in a few cases where only the title is given a mark of explanation is presented.   These marks and their meaning are as follows:

*Foreign language article for which no translation is available
+Article published too recently for review
++Article ordered from various U. S. Government agencies or
    foreign countries but not received in time for review

In many cases double parenthesis have been placed around various comments in the articles. These parenthesis denote inter-jected comments not present in the original article or report but added for clarification, explanation, or for connecting various portions of an article.

Section 3.9 presents references that give detailed and/or extensive information on a number of the isotopes in the bibliography and so are placed there for general examination. Section 3.10 contains a number of references that were reviewed and found to be of limited interest to this investigation. However, they were referenced in the Nuclear Science Abstracts as a direct reference concerning one or more of the isotopes under investigation. Considering, therefore, that almost all of them are government reports it seemed advisable to include them here so as to describe, generally, their contents.

2.4   Best Value Verification. Wherever possible personal telephone calls were made or letters were sent to those people whose papers or articles were cited as best values. This was done for the following purposes.

(1)   To inquire as to whether the experiment had been continued in order to better accuracy.

(2)   To make sure that further experimentation had not negated the values given.

Also, where possible, each of the investigators questioned was asked to comment as to whether he or she considered the value stated a best value.

Inquiries were also directed to those persons that are considered to be authorities in their respective fields to review the best values given for each isotope and to comment on or criticize these values. A list of these persons and their field of interest is as follows:

(1)   Strontium-90   Mr. Thomas Bustard
                           The Martin Company
                           Baltimore, Maryland

(2)   Cesium-134, 137   Dr. G. L. Keister
                           Boeing Company
                           Seattle, Washington

Dr. Leonard A. Dietz
Knolls Atomic Power Laboratories
Schenectady, New York

(3) Promethium-147

Dr. R. L. Moore
H. H. Van Tuyl
Hanford Laboratories
Richland, Washington

(4) Polonium-210

Dr. C. J. Kershner
Mound Laboratories
Miamisburg, Ohio

(5) Plutonium-238

Dr. R. Grove
Dr. J. A. Powers
Mound Laboratories
Miamisburg, Ohio

(6) Curium-242, 244

Dr. E. Lamb
Oak Ridge National Laboratories
Oak Ridge, Tennessee

Dr. R. C. Hoff
University of California
Lawrence Radiation Laboratories
Livermore, California

Mr. H. Diamond
Mr. W. Bentley
Argonne National Laboratories
Argonne, Illinois

3.0   THE ANNOTATED BIBLIOGRAPHY

3.1   STRONTIUM-90

I.   HALF LIFE

27.7 Years ... Ref. 3.1.10   Canad. Jour. Phys. 33
133-7, March to April 1955

II.   ENERGY LEVELS AND DECAY SCHEME

Sr-90 $\underrightarrow{\text{Beta}}$ Y-90

0.54 Mev (100%) ... Ref. 3.1.5   Ann Acad. Sci. Fennicae
Ser A VI, 21, 1-12,
1959

```
0+ ——— Sr-90 ———

           β

2- ————————— 0
     Y-90
```
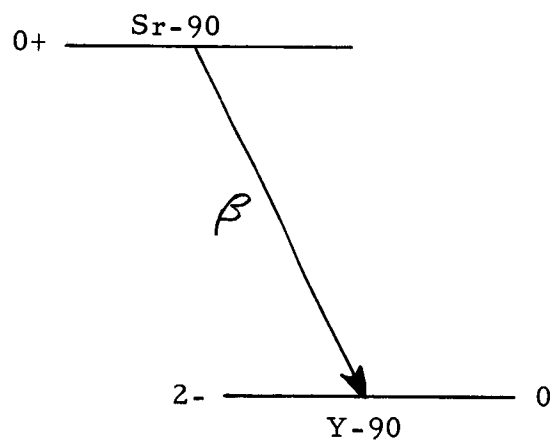
Rev. Mod. Phys. 30,
2, II, April 1958

3.1.1   +BREMSSTRAHLUNG FROM Sr-90, Y-90 IN THIN
         ABSORBERS.   Thomas S. Bustard (Martin Marietta
         Corp., Baltimore, Maryland), Joseph Silverman
         (University of Maryland, College Park, Maryland).
         Paper presented at the Symposium on Low Energy and
         Gamma Sources and Applications.   Oct. 20, 21, 1964,
         Chicago, Illinois.   Sponsored by AEC.

ABSTRACT

The bremsstrahlung yields obtained from targets ranging in atomic
number from 13 to 73 using a thin, point source of Sr-90, Y-90 are
presented.   A novel method of obtaining these yields was used in that
the bremsstrahlung spectra are measured as they are built up and
attenuated through targets whose mass thicknesses are less than the
range of the Y-90 maximum energy beta particle.   The resulting
bremsstrahlung yields are then compared to those calculable from the
Evans** approximation to thick target theory.

**The Atomic Nucleus, Evans, R.D.   McGraw Hill, 1955

3.1.2   ++(ORNL-TM-198) ISOTOPES DIVISION QUARTERLY
         REPORT, OCTOBER-DECEMBER 1961.   J. H. Gillette
         (Oak Ridge National Laboratories, Tennessee).   June 5,
         1962.   Contract (W-7405-eng-26).   39 p.

((PARTIAL ABSTRACT))

Progress is reported on developments in the preparation, properties,
and measurements of radioisotopes, radioactive sources, calutrons,
and thermal diffusion studies in radioactive gases (B.O.G.).   The
feasibility of preparing a Sr-90 heat source, of 8×10^5 curies, was
studied.   Information concerning the status and progress of
engineering development is given.

3.1.3   ISOTOPIC POWER DATA SHEETS.   Compiled by S. J.
         Rimshaw (Oak Ridge National Laboratory, Oak Ridge,
         Tennessee).   For presentation at Industry Information
         Meeting on Isotopic Power Development and Applications,
         Washington, D.C.   May 18-19, 1964

INTRODUCTION

Nuclear and physical properties are listed of some radioactive materials having potential application to terrestrial, marine, and aerospace power requirements. The data here are limited to unclassified source materials of Co-60, Sr-90, Cs-137, Ce-144, Pm-147, Cm-242, and Cm-244. It will be obvious from reviewing the data sheets that experimental information on the properties of radioactive materials is very incomplete. Where such information is not available, literature values derived from the inactive materials or related materials have been used to indicate the probable order of magnitude of the value.

Future data compilations will include more isotopes and materials. The information will be presented in the form of a manual or handbook in order to increase the space available for presenting and evaluating the data that are available. Provisions will be made for additions or deletions of data to keep the information current and meaningful.

Source Material	$SrTiO_3$
Half-life	Sr-90 - 27.7 years (Y-90 - 64.2 hrs)
Decay and Radiation Properties	Sr-90 $\longrightarrow$ Y-90
	$\sim$ 100% beta - 0.54 Mev
	Y-90 $\longrightarrow$ Zr-90 (stable)
	$\sim$ 100% beta - 2.26 Mev
Isotopic Composition	55% Sr-90, 43.9% Sr-88, and 1.1% Sr-86
Activity Concentration	33 curies of Sr-90 per gram of fission product $SrTiO_3$
Radiochemical Purity	> 99.9% Sr-90 + Sr-89. Sr-89 is present in concentrations dependent on length of time since discharge from the reactor and is usually < 5% of the Sr-90 activity at time of fabrication of source pellets. Other radiochemical impurities such as Ce-144 can be neglected.

Chemical Purity	> 95% strontium. Major impurities are Ca and Ba.

Chemical Purity   > 95% strontium. Major impurities are Ca and Ba.

Specific Power   0.223 watts per gram of $SrTiO_3$, or 6.772 watts per kilocurie of Sr-90.

Thermal Energy   148 curies Sr-90 per thermal watt

Density   ~ 3.7 g/cm^3. The theoretical density is 5.0 g/cm^3. Production values vary from 3.2 to 4.2 g/cm^3, averaging about 3.7 g/cm^3.

Power Density   0.825 watts/cm^3 from Sr-90 at a density of 3.7 g/cm^3. Sr-89 will contribute in proportion to its concentration at a rate of 3.4 watts/1000 curies of Sr-89.

Thermal Conductivity   Values reported for inactive $SrTiO_3$ vary from 0.0132 to 0.0173 cal/sec cm $^{\circ}C$ at room temperature, depending on the density.

Coefficient of Expansion   1.12 x 10^{-5} $^{\circ}C^{-1}$

Melting Point   ~ 1900$^{\circ}C$

Mechanical Strength   Fair

Thermal and Radiation Stability   The thermal stability is good. The radiation stability is good as exhibited in two-year old samples.

Radiation Attenuation

Dose Rate, rads/hr at 100 cm	Shielding in Centimeters of Uranium for a Sr-90 Source Strength of		
	100 w	1000 w	10,000 w
100	0.07	0.7	2.0
10	1.0	2.3	3.8
1	2.6	4.3	5.8
0.1	4.4	6.2	8.0

Gas Evolution Due to Radioactive Decay Processes	None
Leach Rate	Inactive $SrTiO_3$ leaches at a rate of 1 microgram/day cm^2 in sea water. Tests on 18-month old pellets of fission product $SrTiO_3$ indicate a leach rate of $\sim$ 1 mg/ day cm^2.
Vapor Pressure	No data available
Resistance to Thermal Shock	No data available
Burnup Characteristics	Dispersibility poor
Capsule Compatibility	Excellent with usual capsule materials such as stainless steel and Hastelloy "C".

((This reference is reproduced in its entirety))

3.1.4   *(CEA-tr-X-355) MESURE DES RAYONS   PAR
L'EMPLOI DES COMPOSES ORGANIQUES FLUORES-
CENTS.   I. MESURE DU SPECTRE DE β A L'AIDE
DES MONOCRISTAUX D'ANTHRACENE.   (Measurement
of Beta Rays by Use of Fluorescent Organic Compounds.
I. Measurement of β Spectra Using Anthracene Mono-
crystals.)   T. Watanabe.   Translated into French from
Oyo Butsuri, 28; 377-80 (1959).   12 p.

ABSTRACT

It has been reported that the light pulse produced by mono-energetic
electrons impinging on anthracene crystals is proportional to the
electron energy within its limited range.   In the present work, the
response of a large single crystal of anthracene to impinging beta rays
emitted by radioactive substances is discussed.   The crystal used is
of cylindrical shape, approximately 2.5 cm in diameter and 3.0 cm in
height.   It is glued with silicon grease to the photocathode of the
Dumont 6292 photomultiplier tube.   Output signals are proportionally
amplified by an A-1 type linear amplifier and are analyzed by a single
channel pulse analyzer.   Beta spectra from pure beta emitting

substances, such as S-35, RaD, RaE, RaF, or Sr-90 + Y-90, are observed and compared with that obtained by a lens type magnetic beta spectrometer with the result that the two spectra are similar except in the low energy part where the intensity of the former is higher. This seems attributable to both the beta bremsstrahlung and the imperfection of the crystal which was colored and opaque. The relation between the maximum energy of the beta rays and the pulse height is of good linearity from 0.16 to 2.2 Mev electron energy. (Auth)

3.1.5   ++ON THE BETA SPECTRUM AND DISINTEGRATION ENERGY OF Sr-90 AND Y-90. Vaino Hovi. Ann. Acad. Sci. Fennicae Ser. A VI, No. 21, 1-12 (1959)

ABSTRACT

Values for the mean energy, $\overline{E}_{beta}$ of the beta particles of the isotopes Sr-90 and Y-90 were determined by using different approximations of the shape correction factor and available spectroscopic data. It is shown that in the case of Sr-90 the theoretical mean energies corresponding to different approximations of the shape correction factor differ so much from each other that by using modern micro-calorimetric techniques at low temperatures it would be possible to get an independent verification of the shape factor. This might be important for clearing up the actual form of the interaction in beta-decay. In the case of Y-90, because of the small relative differences between the values of $\overline{E}_{beta}$, independent calorimetric verification could hardly lead to as significant results. (Auth) ((Detailed information on decay energy was obtained from Mr. T. Bustard, The Martin Company, Baltimore, Maryland.))

3.1.6   *NACHWEIS DER POLARISATION DER BETA TEILCHEN VON Sr-90 + Y-90 by Joachim Heintze, Zeitschrift Fur Physik 148, 560-3, 1957. ((The entire article is in German and no attempt at translation has been made.))

3.1.7   M6472 STRONTIUM-90 BIBLIOGRAPHY. Braden, C.H., L. Slack, and F. B. Spull, Dec. 31, 1957, 10 p.

The following sources were checked for references relating to Sr-90: Chemical Abstracts, Nuclear Science Abstracts, and Library files. ((All applicable references contained in this document are contained elsewhere in this section.))

3. 1. 8   DESIGN AND PERFORMANCE OF A THIN MAGNETIC
LENS BETA RAY SPECTROMETER.   T. D. Nainan,
H. E. Deware, and Ambui Mukerji (Tata Institute of
Fundamental Research, Bombay, India).   Proceedings of
the Indian Academy of Science, 44A, 111-122, 1956

ABSTRACT

Construction of a thin magnetic lens beta ray spectrometer is
described.   A baffle system which takes advantage of the ring focus
has been designed on the basis of the calculations of electron
projectory limited to an angle of acceptance of 9-10.5°.   The results
of the studies of the beta ray spectra of Sr-90 and Y-90, Pm-147,
Tm-170, are presented.

((End of Abstract))

((Source purity: Mixture of Sr-89, 90.   Sr-89 allowed to die down to
negligible intensity.   Sample measured on thin backing of mica.   The
measured beta spectrum is as follows: $E_{beta\ max}$ = 0.541 ± 0.008
Mev.))

3. 1. 9   FORBIDDEN BETA SPECTRA OF Rb-86, S-90, Y-90,
AND Tl-204.   E. E. Berlovick, D. M. Kahai, and A. V.
Savateev.   Izvestia, Akad, Nauk, 20-275-88, March 1956

ABSTRACT

In solving the problem of beta interaction an important part is played
by elucidation of the forbidden beta spectra.   Such investigations are
also of interest in connection with the study of the nuclear shell model.
In the present work we studied the shape of the forbidden spectra of
R-86, S-90, and Tl-204.   All these nuclei have an even mass number
and for them the transitions to the ground state of the daughter nucleus
occur between even-even and odd-odd nuclei, or vice-versa.

((End of Abstract))

The radioactive isotope Sr-90 with a half life of 19. 9 years** is one of
the members of the radioactive chain beginning with Br-90 that is
produced by the bombardment of U-235 with slow neutrons.   Sr-90 is
separated chemically from the disintegration products together with
Sr-89 (half-life = 54. 5 days) after decay of the latter, Sr-90 can be

obtained together with its daughter Y-90 which is formed in the ground state.   Y-20 with a half life of 2.54 days decays to the stable nucleus Z-90 in the ground state.   In our measurements we use samples of Sr-90 with a very high specific activity separated from the uranium disintegration produce and cooled for a sufficient time to insure Sr-89 content under 1a.   The source material was applied in the form of an ultra thin layer on a strip of aluminum foil one micron thick.

**The currently accepted value for the half life of Sr-90 is 27.7 years.

((Cited as best value for decay energy in Rev. Mod. Phys. Vol. 30, #2 Pt. II, April 1958.))

3.1.10   THERMAL NEUTRON FISSION YIELDS AT MASSES 90 AND 91.   George W. Reed (Argonne National Laboratories, Lemont, Illinois).   Physical Review 98, 1327- 9 June 1955

ABSTRACT

Thermal neutron fission yields in U-235 have been determined for Sr-90 and Y-90.   The fission yield at Sr-90 is 4.02 per cent based on a half-life of 20 years.   The yield for Y-91, 5.35%, agrees with experimental error with that previously reported for Y-91.   The apparent low yield at mass 90 is discussed.   ((The discussion of the fission yield at Sr-90 is based on a 19.9 year half life.   The presently accepted value is 27.7 years.))

3.1.11   THE HALF LIFE OF STRONTIUM-90.   D. M. Wiles and R. H. Tomlinson (McMaster University, Hamilton, Ontario, Canada).   Canadian Journal of Physics 33, 133-7, March to April 1955.

ABSTRACT

The value of 27.7 ± 0.4 years has been obtained for the half life of Sr-90 from the absolute disintegration rate of a known number of atoms. The disintegration rate was measured with a 4 pi proportional counter and the number of atoms was determined with a mass spectrometer using isotope dilution.

((The half life determined by these workers is the currently accepted value.))

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3.1.12   REFER TO CS7-3.   FISSION YIELDS OF STABLE AND
            LONG LIVED ISOTOPES OF CESIUM; RUBIDIUM; AND
            STRONTIUM IN NUCLEAR SHELL THEORY.   Canad. Jour.
            of Phys. 31, 419, 1953

3.1.13   FURTHER STUDIES ON Sr-90 and Y-90.   L. E.
            Glenderin and C. D. Coryell, Unclassified, NNES (IV) 9
            Book 2, 687-91, Auth 1951, ANL.

ABSTRACT

Absorption curves of the Sr-90 and Y-90 radiations in aluminum
indicate maximum beta energies of 0.6 Mev for Sr-90 and 2.2 Mev for
Y-90.   The half life of Sr-90 has been estimated from fission-yield
considerations to be 24 to 30 years.   The best values taken at 25 years.
Based on Reports CC-529 and CC-1112 of 1943.

3.1.14   IDENTIFICATION OF Sr-90 AND Y-90 IN URANIUM
            FISSION.   R. W. Nottorf, Unclassified NNES (IV) 9
            Book 2, 682-6, 1951

ABSTRACT

The discovery of a long lived strontium activity and its shorter-lived
yttrium daughter is reported.   The yttrium isotope was identified with
the known 60 hour Y-90 and its half life was shown to be 65 hours.
Decay measurements of Sr-90 over 30 months indicated a period of
23 ± 3 years.

Based on reports CC-521 and CC-725 of 1943.

3.1.15   FIRST-FORBIDDEN-BETA-SPECTRA AND THE BETA
            SPECTRUM OF STRONTIUM-90 - YTTRIUM-90.
            Al Jackson Laslett, E. N. Jensen, and A. Paskin
            (Institute for Atomic Research and Department of Physics,
            Iowa State College, Ames, Iowa).   Physical Review 79,
            412, 1950.

((Author states)) that a more adequately separated source of Sr-90 was
obtained since our first work on this activity**.   Upper limit of 0.54
Mev (kinetic energy) is obtained for the Sr-90 beta spectrum ((the half
life of Sr-90 is taken at 19.9 years in this article.   Presently accepted
half life for Sr-90 is 27.7 years)).

**Phys. Rev. 75, 1949, 1949

3.1.16   THE HALF LIFE OF STRONTIUM-90,   Ruth I. Powers
          and A. F. Voigt (Institute for Atomic Research and
          Chemistry Department, Iowa State College, Ames, Iowa).
          Physical Review 79, 175, 1950**

ABSTRACT

The two samples used, after separation from cyclotron bombarded
Uranyl nitrate, were purified by repeated carbonate precipitations and
mounted as Strontium carbonate.   In order not to measure any of the
55 day Sr-89 which was originally present, sample one was read with
746 mg/cm^2 of aluminum absorber while sample two was read with
714 mg/cm^2.   The decay of several samples which were prepared
have now been followed for seven years by means of a Lauritsen
electroscope and the half life resulting from these measurements is
sufficiently different from that currently used to warrant its
publication at this time.   The method of least squares was used to
draw the best possible straight line through each set of data.   From
this a half life of 20.0 years was obtained with sample one while
sample two gave 19.7 years.   Therefore, the half life of Sr-90 may be
taken as 19.9 ± 0.3 years.   ((This was the original experiment in
which the half life of Sr-90 was determined to be 19.9 years.   The
presently accepted half life of Sr-90 is 27.7 years.))

**Also published as government report No. AECU 840, 1 May 1950.

3.1.17   THE FORBIDDEN BETA DECAY OF STRONTIUM-90 AND
          YTTRIUM-90.   Charles H. Braden, Louis Slack, and
          Franklin D. Shull. (Washington University, St. Louis,
          Missouri.)   Physical Review 75, 1964 - 5 June 1949

ABSTRACT

The isotope Sr-90 is a fission product which decays by beta emission
to Y-90.   The half life is 8×10^8 seconds ((25.4 years)) and the
energy release including rest mass is 2.04 mc^2 (kinetic energy 5.71
kev).   The daughter product Y-90 decays by beta emission to Zr-90.
The half life of this transition is 2.25×10^5 seconds and the energy
release is 5.40 mc^2 (kinetic energy 2.25 Mev).   No gamma radiation
is observed.

((End of Abstract))

A carrier free sample of Sr-90 was obtained from Oak Ridge. This sample had been aged to permit an associated 55 day activity of Sr-89 to die out. Three spectrum were measured. One, Sr-90 and Y-90 in equilibrium together; two Sr-90 alone; and three, Y-90 alone. For the latter two runs, the isotopes were chemically separated by a method due to Kurbatov and Kurbatov. Samples were prepared for the spectrometer by evaporation from solution on thin zapon films following the insulin technique of Langer. The spectra were measured in the double focusing spectrometer described by Kuri, Osoba, and Slack. ((The decay scheme for Sr-90, Y-90 shown in this article is presented as Figure Sr-1.))

3.1.18   SHAPE OF THE BETA-SPECTRA OF STRONTIUM-90 AND YTTRIUM-90. E. N. Jensen and L. Jackson Laslett. (Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa.) Physical Review 75, 1949 - 1949.

ABSTRACT

The beta spectra of Sr-90 and Y-90 have been examined in this laboratory using the magnetic lens spectrometer previously described, and were found to exhibit a shape similar to that recently reported by Langer and Price for the forbidden transition of Y-91. The upper limits found for the Sr-90 and Y-90 spectra are 2.05 mc^2 (0.53 Mev kinetic energy) and 5.37 mc^2 (2.23 Mev kinetic energy), respectively. These values determined in light of the special form found for the spectra differed not inappreciably from those reported by Meyerhoff** whose data also, however, give some indication of the same type of departure from the conventional spectral shape as that reported here.

**Phys. Rev. 74, 621-2, Sept. 1948

3.1.19   ANGULAR CORRELATION OF SUCCESSIVE GAMMA-RAY QUANTA II. Edward L. Brady and Martin Deutsch. (Massachusetts Institute of Technology, Cambridge, Massachusetts.) Physical Review 74, 1541-2, November 1948. ((Article is concerned with the angular correlation observed by an improved method using scintillation counters for six radioactive substances. These substances were nickel, yttrium, magnesium, barium, strontium, and palladium.))

$_{38}$Sr-90 _____ I = O (Even)

T 1/2 = 8.0 x 10^8 sec

$_{38}$Y90 _____

I = O (Even)

Zr-90 Stable
$_{40}$
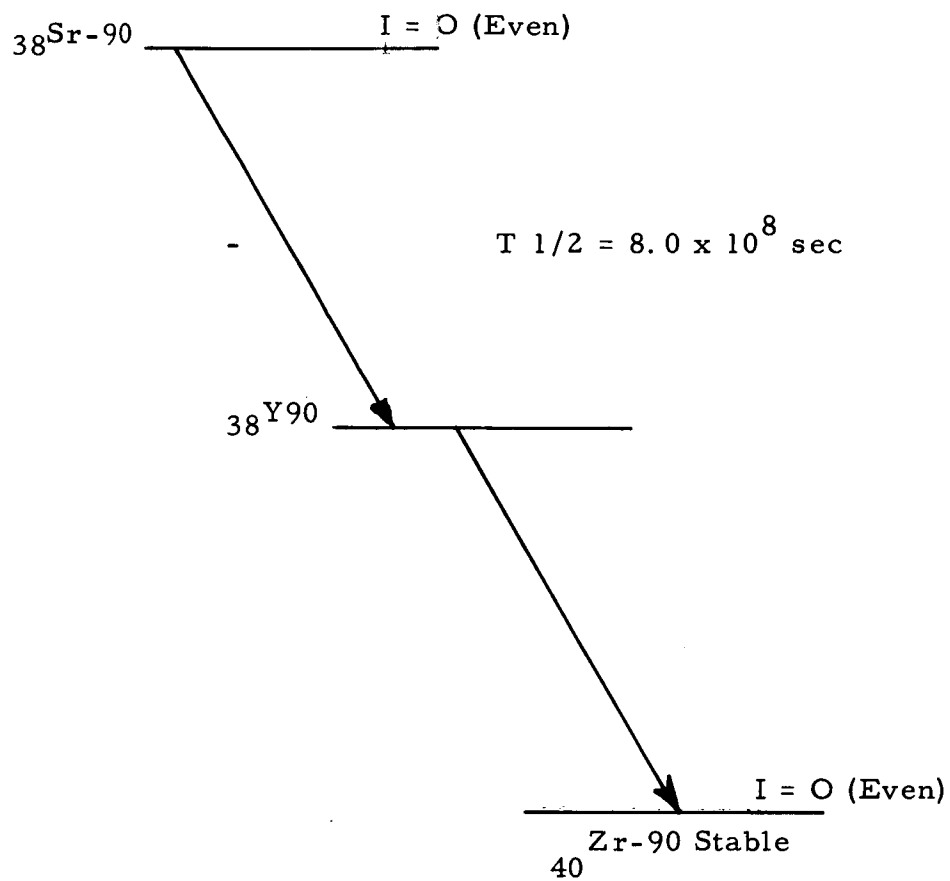
FIGURE Sr-1.   THE DECAY SCHEME OF Sr-90

3.1.20   NOTES ON THE BETA-SPECTRA OF YTTRIUM-90 AND
          STRONTIUM-90.   Walter E. Meyerhoff. (Department of
          Physics, University of Illinois, Urbana, Illinois.)
          Physical Review, 74, 621-2, September 1948.

ABSTRACT

The rather wide discrepancies in the literature values of the beta end
point energy of Y-90 made it desirable to repeat the measurement of
this energy.   Since the Y-90 (60 hours), can be obtained in secular
equilibrium with Sr-90 (25 years) in a practically carrier free form,
the value for the beta end point energy of Sr-90 was obtained also.

((End of Abstract))

Sources of the order of 1 mg/cm^2 thickness were deposited on 0.02
mg/cm^2 thick zapon film and mounted in a conventional 180° type
spectrometer with a Neary slit type system.   An end window geiger
counter carrying a fixed slit which was covered with a 0.8 mg/cm^2
mica window served as a detector.   The resolution of the spectrom-
eter was 3%.   Curie plots of the beta spectra gave 2.35 ± 0.03 Mev
for Y-90 end point and 0.61 ± 0.01 for the Sr-90 end point.

3.2   CESIUM-134

HALF LIFE

Cs-134, 2.050 ± 0.004 years .... Ref. 3.2.8 Anal. Chem.
7, 797-9 June 1963

Cs-134 m, 2.93 ± 0.05 hours .... Ref. 3.2.1 UJV - 1018/
64

ENERGY LEVELS AND DECAY SCHEME

Cs-134 $\xrightarrow{\text{BETA}}$ Ba-134

BETA
0.662 Mev (71%)
0.410 Mev (1%) .... Ref. 3.2.3
0.089 Mev (28%)   Canad. Jour.
Physics 42,
GAMMA
1.368, 1.168, 1.036,   504-18,
0.803, 0.796, 0.605, ... March 1964
0.570, 0.563, 0.475 Mev

Q_{BETA} 2.059 Mev ....

$4^+_{55}\text{Cs}^{134}_{79}$

| | IN | OUT |

4+   1970   28%   31.4%

570   803   1368
17.3   10.5   3.6

89   28%   6.4   1643   1-2%   1.3%

475   1036
1.3

410   1-2%   10.0   4+   1402   88%   90%

796
90

661   71%   8.8   1168   11%   11.8%

563   1168
9.5   2.3

2+   605   103%   97.7%

605
97.7

0+

$_{56}\text{Ba}^{134}_{78}$
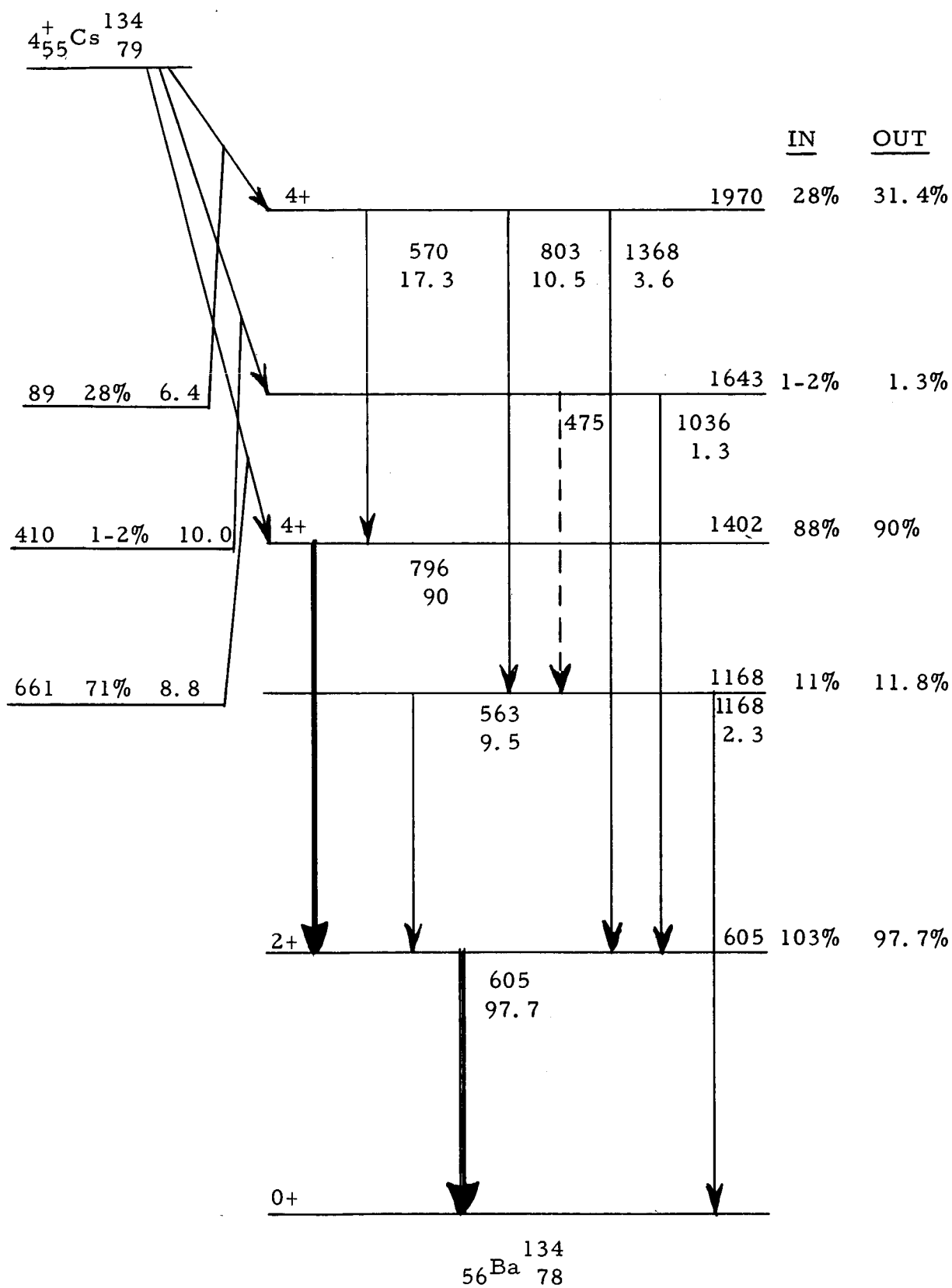
Ref. 3.2.3.   Canadian Journal Physics 42, 504-18 March 1964

3.2.1   *(UJV-1018/64) DECAY OF Cs-134m.   J. Frana, I.
         Rezanka, and A. Spalek (Ceskoslovenska Akademie Ved.
         Ustav Jaderneho Vyzkumu, Rez).   1964, 10 p.

ABSTRACT

The decay of the isomeric state of Cs-134 was studied.   The half life
(2.93 ± 0.05 hours) was determined.   From measurements carried
out by means of a spectrometer with short lens, scintillation measure-
ments, and chemical separations, the non-existence of the weak decay
beta of this state was proved, contrary to statements found previously
in literature (maximum possible intensity 0.02%, against the value of
1% found in literature).   The spectrum of conversion electrons was
measured by a double-focusing spectrometer, and the following
transition energies were determined: 127.3 ± 0.3 kev (E3) and 138.4
± 0.4 kev (M4) (K:L:M + N is 92:100:27 for the 127.3 kev transition,
and 206:100:31 for the 138.4 kev transition).   The K conversion
coefficient of the 127 kev transition was measured, resulting in a value
of 2.55 ± 0.4.   The ratio of transition intensities is $I_{138}:I_{127}$ = 5.7:
1000.   (Auth)

3.2.2   +THE PERFORMANCE OF Au-Si SURFACE BARRIER
         DIODE AS A BETA RAY DETECTOR.   S. K. Sen
         (University of Manitoba, Winnipeg), Nucl. Instr. Methods,
         27:74-6 (Apr. 1964).

ABSTRACT

Pulse height spectra for Cs-134 and Th (B + C + C") were obtained.
The conversion line energies were determined and compared with
other determinations.   The results indicate linear response of the
detector from 150 to 1300 kev.   The internal conversion coefficients
of Cs-134 were also obtained and compared with theoretical values.
(D.C.W.)

3.2.3   THE BETA DECAY OF CESIUM-134.   W. Van
         Wijrgaarden and R. D. Connor (Physics Department,
         University of Manitoba, Winnipeg, Manitoba).   Canadian
         Journal of Physics, Vol. 42, 504-18, March 1964

ABSTRACT

Magnetic spectrometer studies have revealed that the beta decay of
Cs-134 proceeds via three partial spectra whose end point energies,
intensities, and $\log_{10}$ ft values are as follows:

Energy	Intensity (%)	Log_{10} ft
662	71	8.8
410	1	10.0
89	28	6.4

No evidence is found for beta transitions of intermediate energies. Upper limits have been placed on two previously reported beta transitions of higher energy as follows:

Previously Reported Energy and Intensity	Present Work, Upper Limit Intensity
1.453 Mev, 0.2%	0.005%
0.892 Mev, 1.5%	0.045%

These beta intensities to a revised level scheme produce a good balance with the gamma ray intensities depopulating the levels. The Q beta-value is 2.059 Mev.

Source Material	-	Cesium Chloride
Activity Concentration	-	30 curies per gram
Chemical Purity	-	vacuum sublimate onto aluminum foil at low temperature

The Decay Scheme for Cs-134 as presented in this article is shown as Figure Cs4-1.

3.2.4   ++(NP-13020 (p. 53-7)) BETA AND GAMMA RAY SPECTRUM OBSERVED IN THE DECAY OF Cs-134. P. N. Trehan (Punjab University, Chandigarh, India)

ABSTRACT

The decay of 2.19 year Cs-134 leads to the excited levels of Ba-134 by beta emission. This was extensively studied by various workers, but disparity is found in their results. An effort to clarify the situation is presented. Gamma rays from the decay of Cs-134 were measured using a NaI(TI) crystal mounted on a photomultiplier tube and a 20-channel analyzer. A double-focusing magnetic spectrometer was used to analyze the beta spectrum of Cs-134 using a plastic phosphor as a detecting device.

FIGURE Cs4-1.   THE DECAY SCHEME OF Cs-134

3.2.5 *INVESTIGATION OF THE DECAY OF Ba-133 AND Cs-134 BY GAMMA-GAMMA DIRECTIONAL CORRELATION MEASUREMENTS. F. Muennich, K. Fricke, and U. Wellner (Technische Hochschule, Braunschweig, Germany) Z. Physik, 174: 68-90 (1963). (In German.)

ABSTRACT

The directional correlations of the gamma-gamma cascades following the decay of Ba-133 were measured: 355-81, 302-81, 79-81, and 276-160 kev. The results of these measurements together with results of other authors yielded the following well-defined values for the spin of the levels of Cs-133: 7/2+ (ground state), 5/2+ (81 kev level), 5/2+ (160 kev level), 3/2+ (383 kev level), and 1/2+ (436 kev level). The results are discussed in the frame of the shell model. The decay of Cs-134 was investigated by measurement of the gamma-gamma directional correlations: 800-600 kev, 600-600 kev, 1.04-Mev-605 kev. A discussion of these results yielded for the mixing proportion (δ) of the gamma radiation from the transition of the second to first 2+ state in Ba-134 a value $\delta = -0.50 \pm 0.05$ in contradiction to the theory of Davydov and Filippon. Spin 2 was obtained for the 1.64 Mev level of Ba-134; the parity of this state is probably negative.

3.2.6 LEVEL SCHEME OF BARIUM-134. S. O. Schriber, and B. G. Hogg (Allen Physics Laboratory, the University of Manitoba, Canada). Nuclear Physics 48, 647-651, 1963.

ABSTRACT

The gamma ray cascades following the decay of Cs-134 have been examined in using sum coincidence spectrometer. Compton summing peaks have been subtracted using a method developed by the authors. No evidence for the existence of levels at 1846, 1773, and 1570 kev has been found.

((End of Abstract))

All source material was in liquid solution. A small drop of this solution was located at the tip of the 0.5 millimeter wall thickness, 4 millimeter outside diameter glass tube. The source to crystal distance was always 6 centimeters, and the angle between the detectors was maintained at 135° to avoid back scattering. Appropriate shielding was placed so that no part of one crystal could see any part of the other

crystal. ((The Cs-134 decay scheme derived by the authors of this paper is shown as Figure Cs4-2.

3.2.7   *DECAY SCHEME AND MATRIX ELEMENTS FOR THE
          TRANSITION Cs-134 ——→ Ba-134. H. Daniel, J.
          Huefner, and O. Mehling (Max-Planck-Inst. fur
          Kernphysik, Heidelberg). Ann Physik (7), 12:106-12
          (October 1963). (In German.)

ABSTRACT

The decay Cs-134 ——→ Ba-134 was investigated with a double
focusing spectrometer and a beta-gamma circular-polarization
correlation setup. The asymmetry parameter (A) of the correlation
between the 656 kev group and the following gamma cascade was
measured to be A = -0.13 ± 0.02, in good agreement with a value of
Mann, Bloom, and Nagel. **This (A) value implies a ratio (X)
between Fermi and Gamow-Teller contributions to the decay of X =
$0.30 \pm ^{0.04}_{0.03}$ and so a definitely non-vanishing Fermi matrix element.
The breakdown of the isotopic spin selection rule at an atomic number
as large as that of Cs (Z = 55) is not surprising. The transition is
qualitatively discussed in shell model terms. Additional information
is given for the disintegration scheme of Cs-134. The level scheme
of Ba-134 is discussed in terms of the vibrational model. (Auth)

** Phys. Rev. 127, 2134-2137, 1962

3.2.8   HALF LIVES OF CESIUM-137 AND CESIUM-134 AS
          MEASURED BY MASS SPECTROMETRY. L. A. Dietz,
          C. F. Pachucki and G. A. Land (General Electric
          Company, Knolls Atomic Power Laboratories,
          Schenectady, New York). Analytical Chemistry 7,
          797-799, June 1963

ABSTRACT

Mass spectrometric measurements of radioactive decay rates over a
period of 1.5 years indicate a half life of 30.35 ± 0.38 years for Cs-137
and 2.046 ± 0.004 years for Cs-134**. Precisions quoted as standard
deviations are considered to be preliminary values because the
experiment will be continued.

((End of Abstract))

4+   22 Y

$_{55}$Cs$^{134}_{79}$

86 (28%)

410 (1.8%)

658 (70.2%)

4+   1970

803
(11.8)

570
(12.6)

1640

1036
(1.8)

4+   1400

796
(82.8)

2+   1168

1365
(3.6)

563
(9.5)

2+   605

605
(97.7)

1168
(2.3)

0

Stable
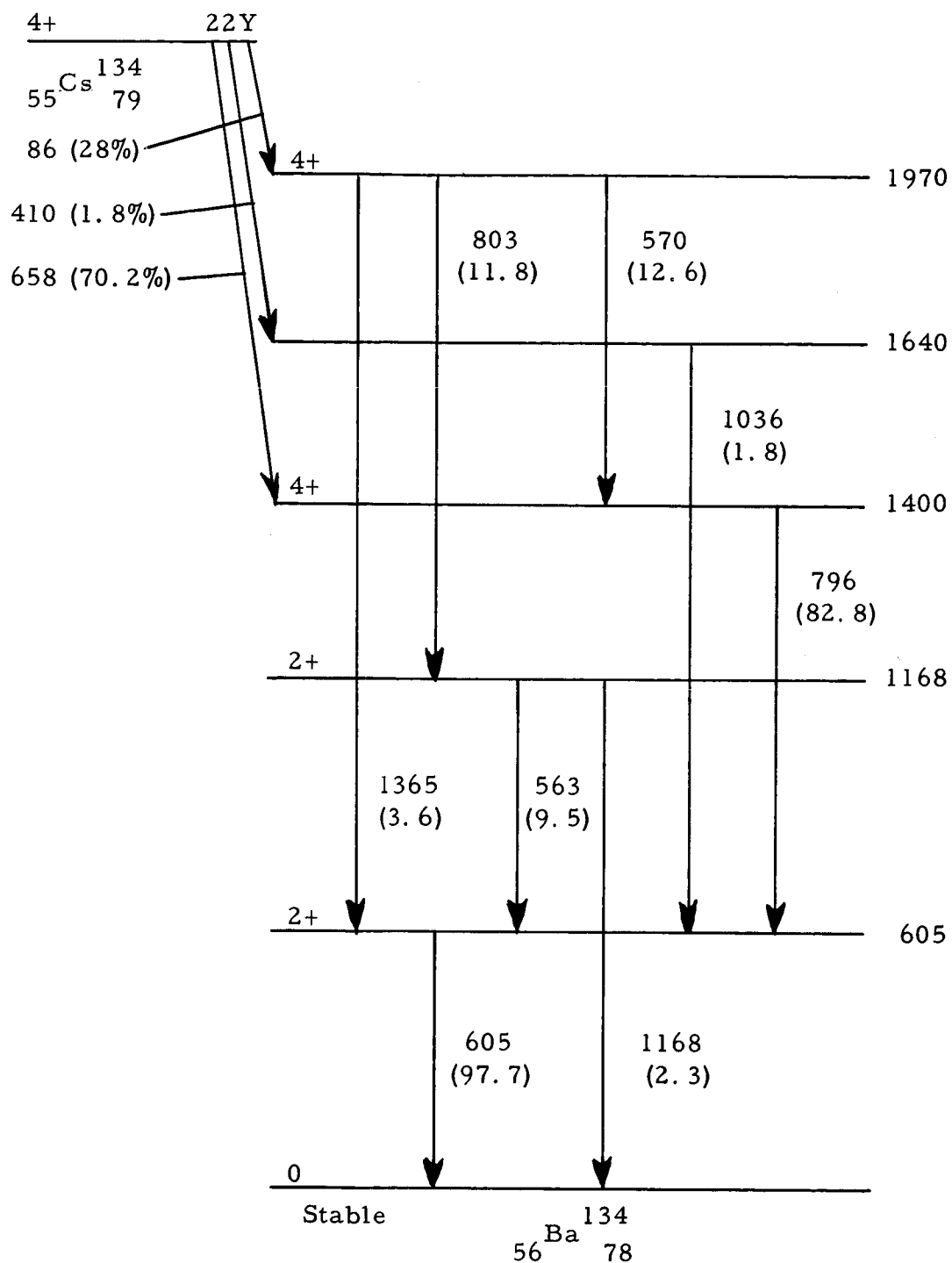
$_{56}$Ba$^{134}_{78}$

FIGURE Cs4-2.   THE DECAY OF Cs-134

27

((Table 3, not shown here, presents published values for the half life
of Cs-137 from 1951 to 1963.   References total ten in number.))   For
the cesium experiment, a batch of six chemically untreated tungsten
V filaments was prepared by outgassing at about 2000°C for more than
one hour in an auxiliary vacuum system.   Each filament was then
loaded with about 1×10^{-8} gram total of the radioactive cesium
isotopes in the form of Cs_2SO_4.   The same procedure was followed
for loading filaments with the Cs-134 stock solution.   ((Table 5, not
shown here, presents the published values for the half life of Cs-134.
These values total seven in number.))

**((The values stated above were revised as a result of a telephone
call to L. A. Dietz on 16 October 1964 to the following values.))

$$Cs-134 \ldots \ldots 2.050 \pm 0.004 \text{ years}$$
$$Cs-137 \ldots \ldots 30.0 \quad \pm 0.38 \quad \text{years}$$

3. 2. 9   CIRCULAR POLARIZATION MEASUREMENTS IN THE
           BETA DECAY OF V-48, Co-56, Fe-59, and Cs-134.
           Lloyd G. Mann, Stewart D. Bloom and R. J. Nagel
           (Lawrence Radiation Laboratory, University of
           California, Livermore, California).   Physical Review
           127, 2134-2137, September 1962

ABSTRACT

The beta-gamma circular polarization angular correlation has been
measured for V-48, Co-56, Fe-59 and Cs-134, using the Livermore
apparatus described previously.   Since all of these decays (with one
exception) are characterized by $J = 0$, $J \neq 0$, and $T \cong 0$, they
possess the necessary elements for testing isospin conservation in
allowed beta decay.   The measured asymmetry parameters are
-0.066 ± 0.035 for V-48, 0.00 ± 0.03 for C-56, -0.074 ± 0.022 for
Cs-134 and -0.23 ± 0.05 and 0.01 ± 0.10, respectively, for the 462
kev and 271 kev beta branches in Fe-59.   These results are
consistent in all cases with a very small Fermi matrix element and
therefore support the validity of isospin conservation with the doubtful
exception of the 271 kev beta decay branch of Fe-59.   However, in
this case, the extreme difficulty of disentangling the 271 kev branch
from the 462 kev branch which is pure Gamow-Teller [3/2 - (beta)
5/2 - (gamma) 7/2] renders this exception rather uncertain.   In the
case of V-48, our result is in disagreement with that of Boehm and
Wapstra who found evidence for sizable interference, but is in better

agreement with the result of Daniel and Kuntze who find evidence for small interference. Our Co-56 result is in excellent agreement with the work of Daniel and Kuntze. Our result for the low energy branch of the Fe-59 decay ($\Delta J = 0$) is in accord with the work of Foster and Sanders, the accuracy being, however, very poor in both measurements. With regard to the high energy branch ($\Delta J = 1$) our result is lower by a factor of 2 than that of Forster and Sanders. Our Cs-134 result shows definite interference but because of the large ft value, the Fermi matrix element is still very small in keeping with the other findings at this laboratory.

((Article mentions only that cesium sources were purchased from commercial suppliers. All sources were mounted on uncoated mylar films of 1 mg/cm^2 by solution evaporation.))

3.2.10   LOW-LYING ENERGY LEVELS OF CESIUM-134. I. V. Estulin, A. S. Melioransky and L. F. Kalinkin (Research Institute of Nuclear Physics, Moscow State University, Moscow). Nuclear Physics 16, 168-74, April 1960

A study is made of the cascade gamma transitions following thermal-neutron capture in cesium nuclei. Energy and quantum characteristics of low lying excited states of Cs-134 with excitation energy up to 320 kev are determined.

((A luminescent coincidence spectrometer worked out by one of the authors of the present paper was used for measuring cascade gamma quanta. The spectrometer consists of the governing and the main channels with a NaI(Tl) crystals and a photomultiplier as gamma ray detectors.))

3.2.11   DECAY OF CESIUM-134. John D. French, and Max Goodrich (Louisiana State University). American Physical Society Bulletin, 4, 391, 1959

ABSTRACT

The gamma rays in the decay of Cs-134 (2.2 years half life) have been studied with a scintillation spectrometer employing a cylindrical (3 inch by 3 inch) crystal of NaI (Tl) and with a coincidence spectrometer using two such crystals in the spectrometers. The pulse spectrum in coincidence with the peak corresponding to each of the gamma rays was obtained. The data indicate that at least 15 gamma

rays were present, all of which occur in the nucleus of Ba-134 following negatron decay, and none occur in the nucleus Xe-134 following positron decay. Previously unreported cross-over transitions of 1640 and 1970 kev, confirming these energy levels were observed. A decay scheme with energy levels in Ba-134 at 605, 1038, 1168, 1367, 1401, 1640, and 1970 kev were presented.

3.2.12   THE LEVEL SCHEME OF BARIUM-134.   SOME FEATURES OF THE SODIUM IODIDE SUMMING SPECTROMETER.   R. K. Girgis and R. Van Lieshout, Nuclear Physics 12, 672-688.   September 1959

ABSTRACT

A detailed analysis of the gamma ray spectrum from Cs-134 was performed. The results are in agreement with previous measurements but two additional weak gamma rays of 960 and 1570 kev were found. Summing peaks of 1.17, 1.40, 1.57, 1.64, 1.77, and 1.97 Mev were observed, establishing the presence of levels of these energies in Ba-134. The gamma ray spectrum from the decay of La-134 was also examined. Only one gamma ray of 605 kev was observed, thus confirming that the first 2+ level in Ba-134 has this energy. Some features of the NaI summing spectrometer are demonstrated and discussed in an appendix to this report.

((End of Abstract))

((Figure 6 of the article presents the proposed level of Ba-134.)) The energy values written on the left-hand side of the various transitions represent the gamma rays following the decay of Cs-134. The numbers in brackets represent their relative intensities in percentage per disintegrations assuming all disintegrations to go through either the 605 or the 1170 kev transitions. The uncertain 605 kev transition de-exciting the level at 1170 kev is drawn in as a dashed line. The characteristics of the beta branches following the decay of Cs-134 in those following the decay of La-134 are shown on the graph in the following order: Energy of the Branch, Intensity and Percentages per Disintegration, and the Log ft value. These values are calculated from the various gamma ray populating and de-exciting levels. ((Figure 6 is presented as Figure Cs4-3.))

3.2.13   GAMMA RADIATION FROM CESIUM-134.   B. S. Dzhelepov, V. P. Prikhodtseva and Yu. V. Hhol'nov. Izvestia Nauk, SSSR, Vol. 23, 826-7, July 1959

4+ 2.2y $_{55}$Cs$^{134}_{79}$

0.068 27%
6.2

1970   1970 (4$^+$)

569 801 1370
(10) (10) (33)

1770

605 1170
(0.5)

0.410 3% 96

1641

475 1040

1570

960 570 (1.3)(1.5)
(0.6)(0.12)

0.652 66% 88

1401 (4$^+$)

796
(80)

1168 (2$^+$)
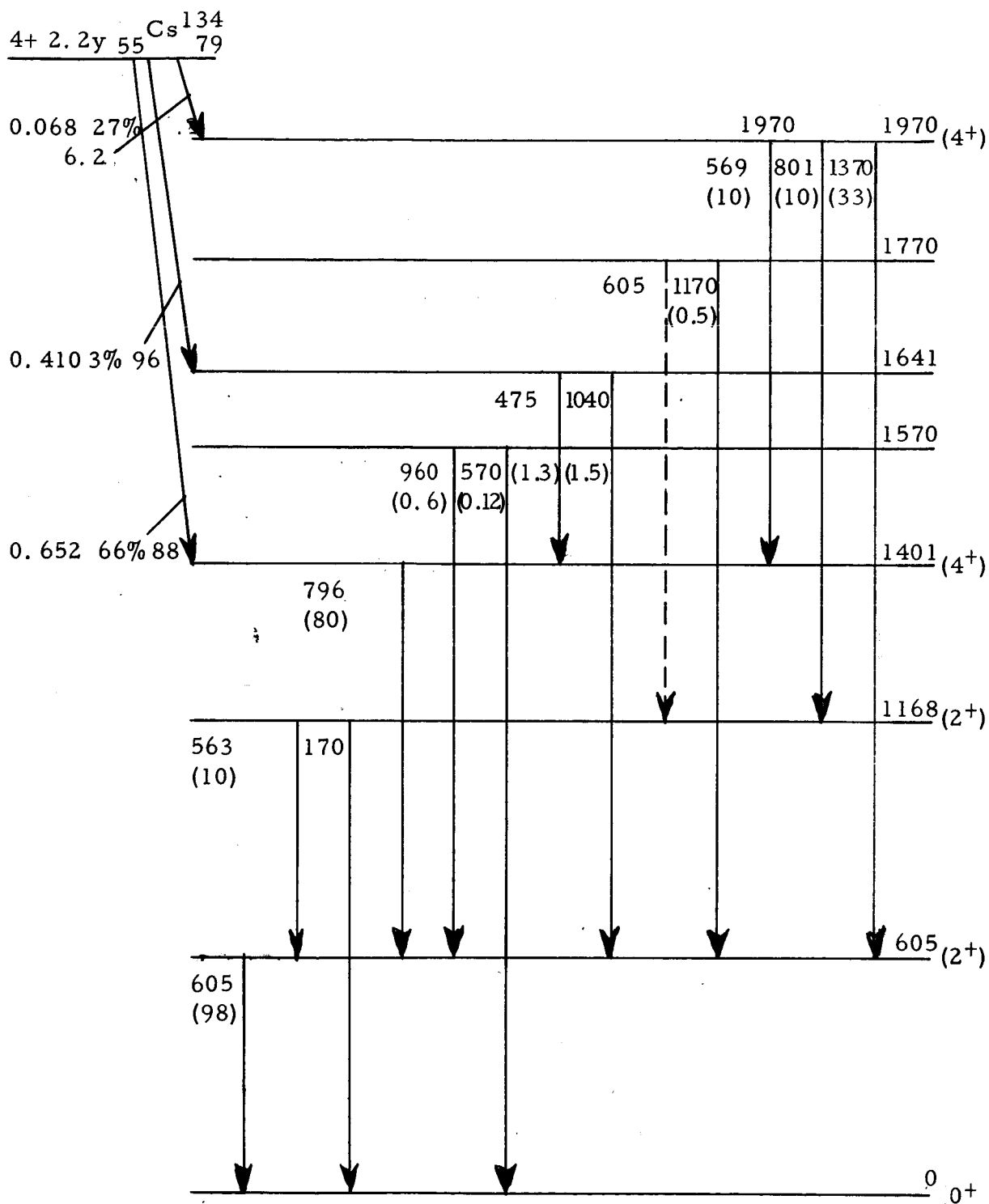
563 170
(10)

605 (2$^+$)

605
(98)

0
0$^+$

FIGURE Cs4-3.   PROPOSED LEVEL SCHEME OF Ba-134

((Article references the energies and relative intensities of the gamma rays from Cs-134 measured during the experiments described in the article.)) Energy of the gamma rays in kev 475, 567, (565 or 571), 606, 663, 797, 1038, 1168, 1368. Relative intensity of the gamma 2.5 ± 0.5, 28.0 ± 3, 10 ± 3 or 18.0 ± 3, 100, 0.5 ± 0.3, 101 ± 4.3, 1.16 ± 0.04, 2.26 I 0.08, 3.79 ± 0.15.

3.2.14   INVESTIGATION OF CESIUM-134 BY THE COINCIDENCE METHOD. Iu. A. Leleksandrov. Izvestia Akad Nauk, SSSR, 827-30, July 1958

This investigation was undertaken for the purpose of investigation of the gamma-gamma and beta-gamma coincidences for the purpose of refining the decay scheme. Our measurements substantiate the existence of the 605-797, 605-1370, 605-570, 797-570 and 1170-802 (797) kev cascade transitions. Our results also indicate the existence of the following cascades: 605-1040 and 1170-475 kev. We also investigated the high-energy region of the Cs-134 gamma spectrum. We observed photo peaks from gamma rays of 1640, 1750, 1870, 1960, and 2040 kev energy. The intensity of all these gamma rays is of the order of 10^{-6} photons per disintegration. All our experimental data on beta-gamma coincidences and the hard part of the Cs-134 gamma spectrum are consistent with the decay scheme proposed by Foster and Wiggins**. (The relative intensities of the cascade transitions according to our evaluations are as follows: 605-797 kev, 100%. 605-570 kev, 10%. 605-1370 kev, 3%. 605-1040 kev, 3%. 797-570 kev, 10%. 1170-805 kev (797), 3%. 1170-475 kev, 2%.)

**Nuovo Cimento 2, 854, 1955

3.2.15   THE CROSS SECTION OF THE REACTION CESIUM-134 (N. GAMMA) CESIUM-135, AND THE HALF LIFE OF CESIUM-134. J. G. Bayly and F. Brown (Atomic Energy of Canada, Ltd., Chalk River, Ontario), and G. R. Hall and A. J. Walter (Atomic Energy Research Establishment, Harwell Didcot, Berks). Journal of Inorganic and Nuclear Chemistry 5, 259-263, 1958

ABSTRACT

The isotopic composition of cesium samples which have been subject to intense reactor neutron radiation was measured with a 6-inch radius 60° sector field, mass spectrometer fitted with a triple filament

thermal ionization source.   The cross section of the reaction Cs-134 (n, gamma) Cs-135 was calculated from the observed isotopic composition and found to be 134 ± 12 barnes.   By measuring the change with time of the Cs-134/(Cs-134 + Cs-135) ratio using the mass spectrometer, the half life of Cs-134 was found to be 2. 15 + 0. 08 - 0. 04 years. In a subsidiary experiment the cross section of the reaction Cs-133 (n, gamma) Cs-134 was found by activation to be $30. 4 \pm 1. 7$ barnes.

((End of Abstract))

Two long irradiations were carried out.   The first was approximately 10 milligrams of spectroscopically pure Cs_2CO_3 in the M. T. R., Idaho for 140 days.   The second was of approximately 10 milligrams of $CsNO_3$ in the NRX reactor, Chalk River for 356 days.   Two short irradiations were made, each of 16 hours, using a position in NRX similar to that used for the long irradiations.   For these irradiations the cesium compounds which were of spectroscopic purity were dried at $110^{\circ}C$ weighed into silica tubes which were then sealed. CsC_2, 36. 8 milligrams was used in the first irradiation, and Cs_2CO_3, 32. 1 milligrams in the second.

Results: The half life of Cs-134.   The decay of Cs-134 is shown by the data of Table I ((Table I is not shown)).   The error shown for the Cs-134 percentages are based on the standard deviation between spectrograms.   The half life of Cs-134 obtained from these data is 2. 15 + 0. 08 - 0. 04 years.   The value obtained by Merritt, et al[**] using a 4 pi proportional beta counter over a period of 5 years is 2. 19 $\pm$ 0. 02 years.   This latter value was used in our calculation because owing to the longer period over which decay was studied it should be more accurate.   Our value of 2. 15 years is a useful confirmation of Merritt's result since the mass spectrometer value is not affected by the problem of radio chemical purity.

[**]Canadian Journal of Physics 35, 16, 1957

3. 2. 16   HALF-LIFE DETERMINATION OF SOME RADIO NUCLIDES.   W. F. Merritt, P. J. Campion and R. C. Hawkings, Canadian Journal of Physics, 35, 16-20, 1957

ABSTRACT

The half lives of the following nuclides have been determined by absolute counting techniques using a pi beta proportional counter.   The

period over which the observations were made is indicated by brackets. The errors quoted are the statistical counting errors.   Na-22, 2.58 ± 0.03 years (2 years); Ru-106, 1.02 ± 0.01 years (5 years); Cs-134, 2.19 ± 0.02 years (5 years); Ce-144, 285 ± 2 days (4 years); Pm-147, 2.64 ± 0.02 years (4 years); Tl-204, 3.56 ± 0.05 years (4 years). ((A review of previous determinations is included in the article.))

3.2.17   RAPID ANALYSIS OF GAMMA EMITTERS USING A
            GAMMA RAY SCINTILLATION SPECTROMETER I.
            QUANTITATIVE ANALYSIS OF CESIUM-134 - CESIUM-
            137 MIXTURE.   Fumio Aoki, Toshio Kurosawa and Seishi
            Yajima.   (Chemical Society of Japan (Bulletin)) 30, 583-5
            Sept. 1957

ABSTRACT

Rapid determination of individual species in a mixture radio nuclides will be required in many cases such as processing of fission products, activation analysis, and chemical, biological, or metallurgical experiments with several kinds of radio nuclides.   The authors have been investigating the possibility of quantitative determination of two nuclides which cannot be resolved by the spectrometer.   This report is a result of the study on Cs-134 - Cs-137 mixture.

((End of Abstract))

The chemical form of cesium was cesium chloride in aqueous solution. It was diluted to about 0.1 microcuries/milliliters with demineralized water.

3.2.18   HALF LIVES OF Sc-46, Co-60, Zn-6s, Ag-110m, Cs-134,
            and Eu-152, 194.   K. W. Geiger (Division of Applied
            Physics, National Research Council, Ottawa, Canada).
            Physical Review, 105, 1539-40, March 1957

ABSTRACT

The half-lives of six gamma emitting nuclides were determined by comparison with radium standards using a lead shielded ionization chamber. The following results were obtained: Sc-46, 83.89 ± 0.12 days; Co-60, 5.24 ± 0.03 years; Zn-65, 243.5 ± 0.8 days; Ag-110m, 252.5 ± 1.5 days; Cs-134, 2.07 ± 0.02 years; Eu-152, 154, 12.2 ± 0.2 years.   The errors quoted are twice the standard deviation calculated from a least squares analysis.

((End of Abstract))

The investigated nuclides were produced by neutron radiation of the Chalk River NRX reactor. The initial activities of the samples were between 100 and 300 millicuries. Details on composition and purity are given in Table I ((presented in part below)). The gamma radiation was measured with a one-atmosphere air-filled parallel plate ionization chamber made of aluminum and shielded by a 0.6 centimeter of lead. Saturation properties were studied by the two-source method but no effects within the experimental errors of $0.0 \pm 0.15\%$ could be found. ((Contents of Table I. Half lives of several gamma emitting nuclides)) Nuclide, Cesium-134; sample, spec-pure. Cs_2AlF_3; decay followed over half lives, 0.8; half life, 2.07 ± 0.02 years; previous measurements 2.3 ± 0.3 years; 1.7 ± 0.1 year. ((End of Table))

((Note on Table I. Cs-134. Although the decay of Cs-134 has not been followed for a full half life, the present value is much more accurate than the figures published previously.)) ((Cited as best value in Rev. Mod. Phys. Vol. 30, #2, Pt. II, April 1958.))

3.2.19   STUDIES WITH SCINTILLATION COINCIDENCE SPECTROMETER: Cs-134. Girish Chaudra (Tata Institute of Fundamental Research, Bombay, India). Proceedings of the Indian Academy of Science A44, 194-200, 1956

ABSTRACT

The set-up of slow fast coincidence scintillation spectrometer is described. Gamma-gamma coincidences in Cs-134 have been studied. The 604-kev gamma transition is found to be in cascade with 460 ± 20, 555 ± 15, 794 ± 15 and 1349 ± 30 kev gamma transitions. The 794-kev gamma transition is found to be in cascade with 604 ± 10 and 555 ± 15 kev gamma transitions. The results are consistent with the decay scheme of Cs-134 proposed by Forster**.

**Nuovo Cinemto, 2, 854, 1955.

3.2.20   HIGH ENERGY FORBIDDEN BETA RAY TRANSITIONS FROM Cs-134 (2.3 years), Co-60 (5.3 years), Sc-46 (84 days), and Hg-203 (47.9 days). J. L. Wolfson, Canadian Journal of Physics, 34, 256-64, March 1956

ABSTRACT

Beta ray transitions of energies 1478 ± 6 kev from Co-60 (5.3 years) and 1475 ± 6 kev from Sc-46 (84 days) were observed with intensities

of $(1.0 \pm 0.2) \, 10^{-4}$ and $(3.6 \pm 0.7) \, 10^{-5}$ beta rays per disintegration, respectively. Forbidden spectrum shapes were obtained for both transitions. No evidence was obtained for the beta ray transition of energy 1451 kev from Cs-134 (2.3 years) nor for the transition of energy 473 kev from Hc-203 (47.9 days) and upper limits of 5×10^{-5} and 3×10^{-4} beta rays per disintegration, respectively, are placed upon the intensities of these transitions. The log ft values are greater than 14.5, 14.0 ± 0.1, 13.0 ± 0.1 and greater than 11.3 for the transitions referred to from Cs-134, Co-60, Sc-46, and Hg-203, respectively.

((End of Abstract))

The sources were all prepared by neutron irradiation in the NRX reactor. In general, the sources were prepared by evaporation of salts from nitric acid solution on backings of 2.3 milligrams/cm^2 aluminum foil. The sources were all approximately 2 millimeters in diameter. The Cs-134 source was about 9 milligrams/cm^2 thick and about 0.75 millicuries in activity.

3.2.21   INTERNAL CONVERSION COEFFICIENTS OF Ba-134, V-51, and Tl-203. Z. O'Friel and A. H. Weber (St. Louis University, St. Louis, Missouri). Physical Review 101, 1076-8. February 1956

ABSTRACT

The internal conversion coefficients of Ba-134 (Parent - Cs-134) V-51 (Parent - Cr-51) and Tl-203 (Parent - Hg-203) have been measured by the determination of the gamma ray yields from the Compton electron spectra produced in an external converter employing the analysis of R. G. Thomas and T. Lauritsen and a single magnetic lens beta ray spectrometer. The Ba-134 results involve the extension of the method to several gamma ray conversions measured simultaneously. V-51 represents the application of the method to K capture type of decay for which the direct area under curves method cannot be used. Tl-203 required the correction of the measured conversion spectrum for photoelectric conversions to obtain the pure Compton events. The values obtained for the total internal conversion coefficients are Ba-134: 569 kev gamma ray, $(9.2 \pm 1.2) \, 10^{-3}$; 605 kev gamma ray, $(5.3 \pm 0.5) \, 10^{-3}$; 796 kev gamma ray, $(2.4 \pm 0.3) \, 10^{-3}$; 1.367 kev gamma ray, $(0.49 \pm 0.05) \, 10^{-3}$; V-51: 3.25 kev gamma ray, $(1.5 \pm 0.2) \, 10^{-3}$; Tl-203: 279 kev gamma ray for K shell $(1.5 \pm 0.1) \, 10^{-1}$ and $(4.9 \pm$

0. 2) 10^{-1} for the L shell. In all cases, the precision is the standard deviation. The results are in satisfactory agreement with other experimental values and with predictions of Rose's Tables. ((All samples obtained from Oak Ridge.))

3.2.22 GAMMA-GAMMA DIRECTIONAL CORRELATIONS IN CESIUM-134. A. E. Everett and J. J. Glaubman (Princeton University). Physical Review 100, 955, 1955

ABSTRACT

We have found the directional correlations of the 1. 37 - 0. 605, 1. 17 - 0. 801, and 0. 796 - 0. 605 Mev cascades in the decay of Cs-134 to be given by: A-2 = 0. 107, 0. 095, and 0. 111, ± 0.015; A_4 = 0. 015, 0. 006, and 0. 016, ± 0.02, respectively. All of these values are consistent with 4-2-0 cascades and agree with the decay scheme suggested by Cork, et al**. In this case, the five observed gamma rays are E2, the excited state of Ba-134 are at 0. 602 (2+), 1. 17 (2+), 1. 40 (4+), and 1. 97 (4+), Mev, and the 0. 563 Mev E-2 transition is between the second and first excited states, and is speeded up by a factor of 15 comparative cross over. All this is very typical to even-even nuclei in this region. However, the decay scheme of the Washington group can not be completely excluded since a 4-2-0 directional correlation can also be interpreted as due to a 3-2-0, 3-1-0, or 2-2-0 cascade, in which the first transition is mixed.

**Phys. Rev. 90, 444-7, 1953

3.2.23 DECAY OF CESIUM-134. H. H. Forster, and J. S. Wiggins (Department of Physics, University of Southern California, Los Angeles, California). Nuovo Cimento, Vol. 2, No. 4, October 1955

ABSTRACT

The beta spectrum and internal conversion electrons of Cs-134 were obtained with a double thin lens beta ray spectrometer. The detector was a conventional type geiger-mueller counter with a replaceable end window. Thin nylon films, 10-50 micrograms/cm^2 thick were used as counter windows. The radioactive source material was cesium chloride in hydrochloric acid solution obtained from Oak Ridge. Thin uniform sources, 10-25 micrograms/cm^2 were deposited on nylon or tygon films by the usual evaporation methods and the films were

supported by a lucite cylinder the sides of which had been cut so as to leave only a narrow range held by four thin strips. The resolution of the instrument was varied between 1.5 and 2.3%, except in the investigation of the end point of the highest energy beta component when a resolution of 3.5% and a source up to 50 micrograms/cm^2 were used. Figure 1 of this article, the decay scheme of Cs-134 is presented as Figure Cs4-4.

3.2.24   ANGULAR CORRELATION OF THE GAMMA RAYS OF BARIUM-134.   M. G. Stewart, R. P. Scharenberg, and M. L. Wiedenbeck (Department of Physics, University of Michigan, Ann Arbor, Michigan).   Physical Review, 99, 691-4, August 1955

ABSTRACT

The angular correlations have been measured between the following pairs of gamma rays from Ba-134: 605 kev - 797 kev, 1368 kev - 605 kev, and 570 kev - 605 kev. These measurements indicate that the spins associated with these gamma rays are 4, 4, 2, 0. The 605, 797 and 1368 kev gamma rays are pure quadrupole while the 570 kev gamma ray is a mixture of 94% quadrupole and 6% dipole.

((Figure 1 of this article, a simplified decay scheme of Cs-134, is presented as Figure Cs4-5. The numbers in parenthesis are the spins of the nuclear levels.))

3.2.25   RADIOACTIVITY OF CESIUM-134.   G. Bertolini, M. Bettoni, and E. Laszarina.   (I. Stieuto Di Fisica, Sperimentale del Politecin - Malino).   Nuovo Cimento, Vol. 11, No. 2, 273, August 1955

ABSTRACT

The beta decay of Cs-134 and the gamma decays of Ba-134 have been investigated with an intermediate image beta spectrometer and a scintillation spectrometer. From beta-gamma coincidences, a new beta decay of 335 kev end point has been revealed and the existence of a weak beta decay on the 1350 kev level of barium has been confirmed. From beta-gamma and gamma-gamma coincidences and from internal coefficients, the relative intensity of the beta decays and the multipolarity of the gamma transitions have been investigated. The five excited states of Ba-134 are assumed having energy of 795, 1350, 1395,
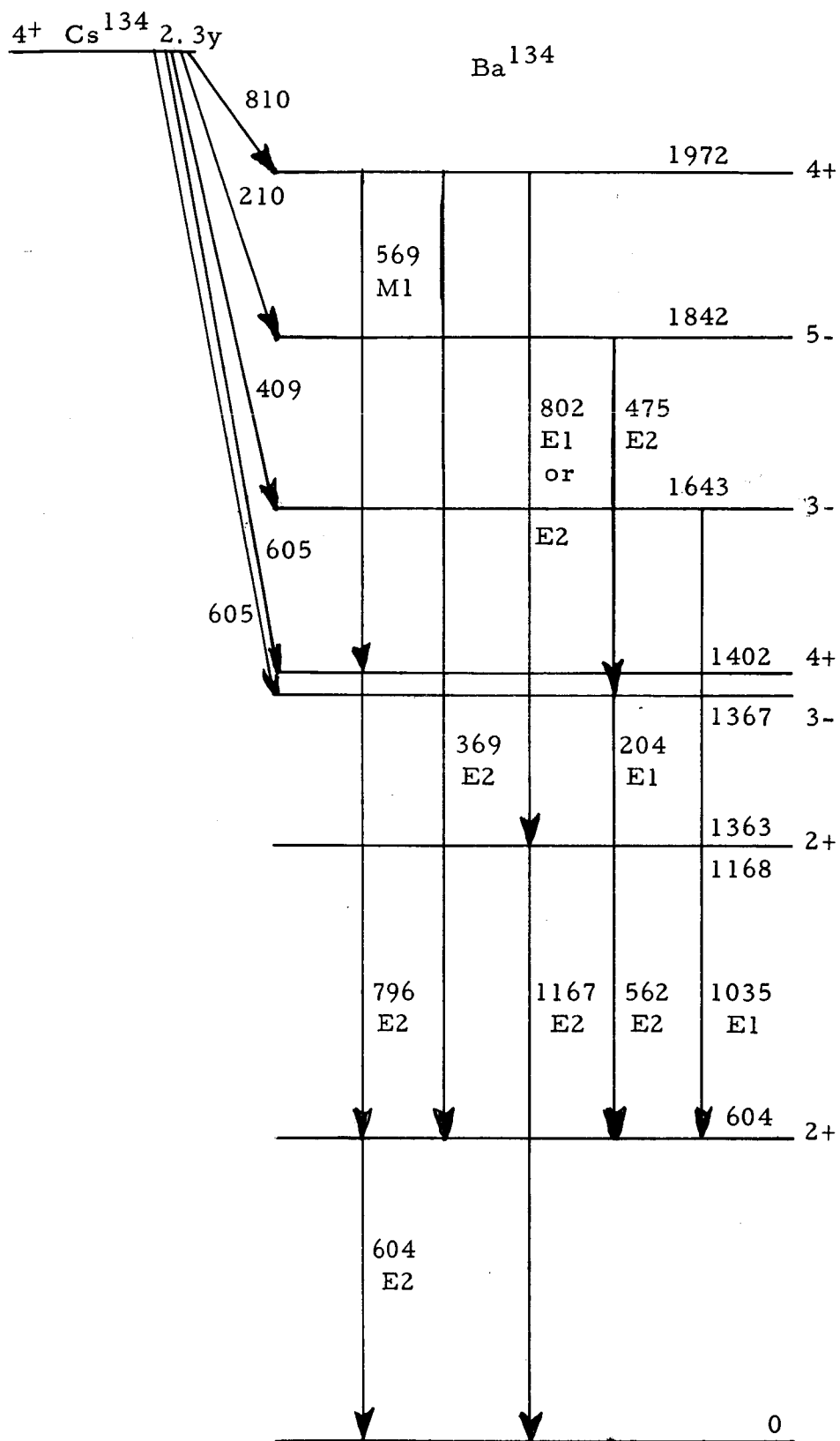
FIGURE Cs4-4. PROPOSED DECAY SCHEME FOR Cs-134
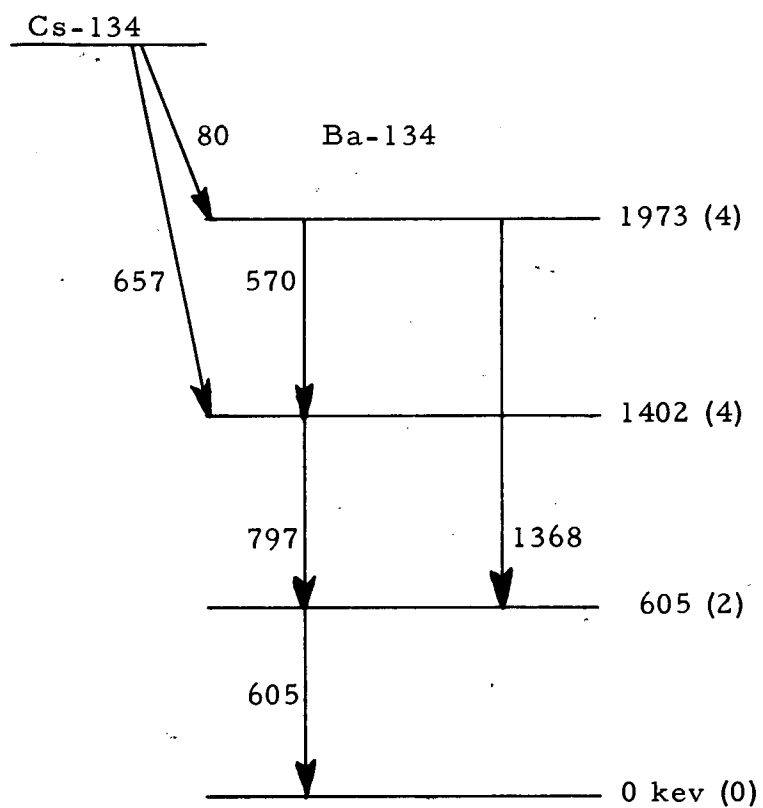
FIGURE Cs4-5.   SIMPLIFIED DECAY SCHEME OF Cs-134

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1700, and 1949 kev. Their spins and parity are 2+, 2+, 3+, or 4+, 3+, or 4+, and 4+.

((End of Abstract))

Cs-134, 5.6 millicuries/grams specific activity, was supplied from Harwell. It was mounted on nylon film of 0.16 mg/cm^2 and, in order to study carefully the beta spectrum shape, it was evaporated under vacuum on the aluminum foil 1 micromillimeter thick. To investigate the beta spectrum a source of about 1 microcurie was used. A source of about 10 microcuries was used for gamma-gamma and beta-gamma coincidences, and for internal and photoelectric conversion. ((Table 1 of this article, not reproduced, presents a summary of the work of seven authors on the following information: beta decay energy in kev, gamma decay energy in kev and conversion coefficient.)) ((The decay scheme proposed by this article is presented as Figure Cs4-6.))

3.2.26   ON THE DECAY OF CESIUM-134. G. Bertolini, M. Bettoni and E. Lazzarini. Nuovo Cimento 10, 1, 746-8, April 1955

Cs-134 is known to decay by beta emission on excited states of Ba-134. Several measurements have been made on the energy of the gamma rays and on the beta ray spectrum with scintillation and magnetic spectrometers. A continuous spectrum shows a low energy component (about 90 kev) and two high energy components (about 650 kev), the in points of which differ by 30 $\div$ 40 kev. We have investigated the beta decays in coincidence with gamma rays of different energies with an intermediate image beta ray spectrometer with NaI(Tl) crystal. A complete description of the beta-gamma and gamma-gamma coincidence is going to be published soon**.

**Nuovo Cimento, Vol. 11, No. 2, August 1955.

3.2.27   RADIOACTIVE DECAY OF CESIUM-134 AND CESIUM-134m.
           G. L. Keister, E. B. Lee and F. H. Schmidt (Department
           of Physics, University of Washington Seatlle, Washington))
           Physical Review 97, 451, February 1955

ABSTRACT

The radiations of Cs-134 (2.3 years) and Cs-134m (3.15 hours) have been studied in a high resolution beta ray spectrometer. The gamma
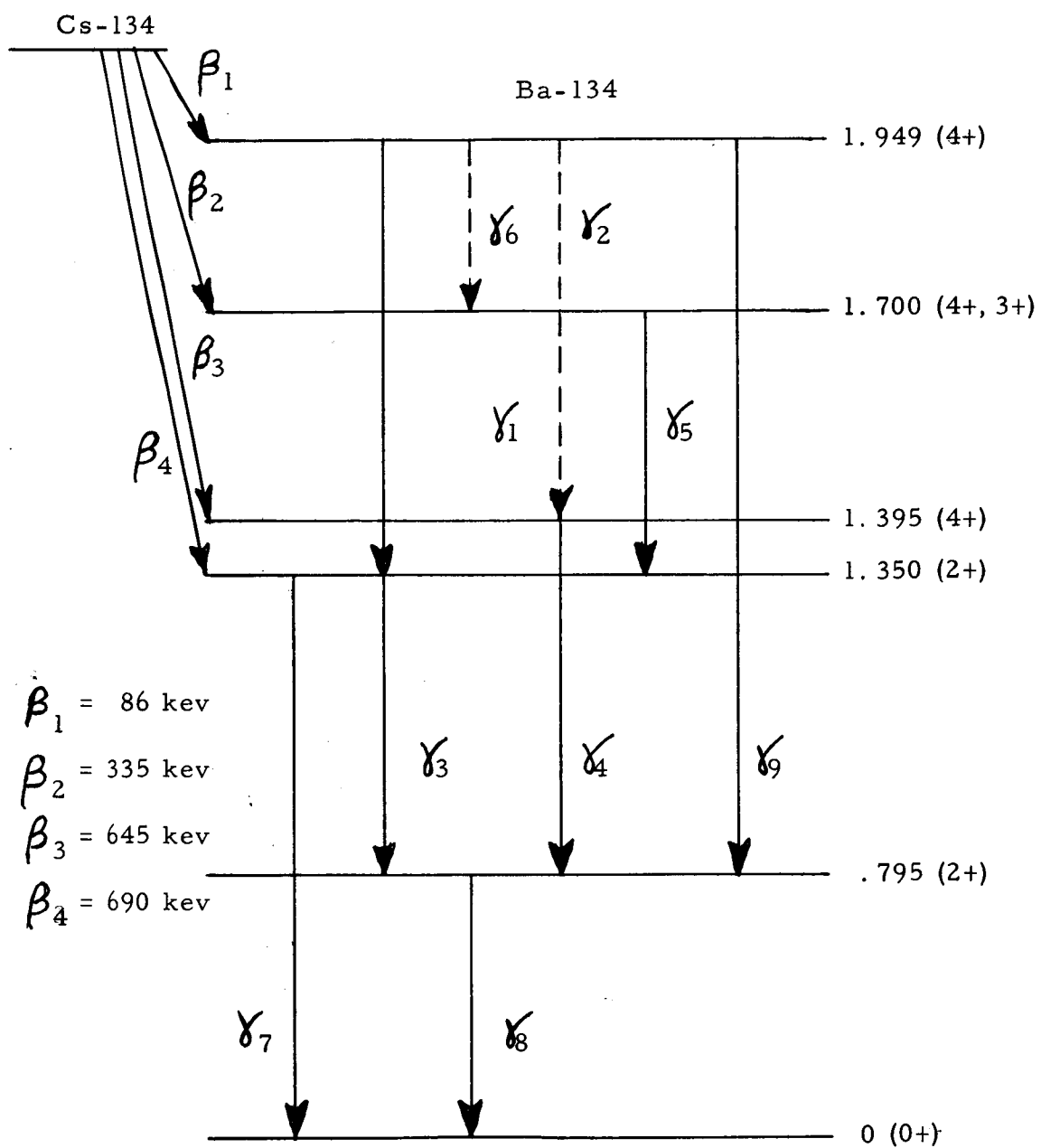
FIGURE Cs4-6.   PROPOSED LEVEL SCHEME FOR Cs-134

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rays of Cs-134 were observed by internal and external conversion, and coincidence rates were measured between the beta continuum and the internal conversion electrons of the stronger gamma rays. The beta spectrum of Cs-134 appears to consist of 4 or possibly 5 components. Nine gamma rays were found both by internal and external conversion; a tenth gamma ray appears only in internal conversion. The decay scheme ((shown as Figure Cs4-7)) is proposed which is reasonably consistent with the multipole order of each of the radiations as obtained from internal conversion data. A search was made for a ground or intermediate state beta transition from Cs-134m. No transition to the ground state was observed. But, some indication was found for a weak transition to an excited state.

3.2.28   GAMMA RAY ENERGIES IN THE DECAY OF CESIUM-134.
M. C. Yoshi, and B. V. Thosar (Tata Institute of
Fundamental Research, Bombay, India).   Physical
Review 96, 1022-3 November 1954

ABSTRACT

The photoelectric conversion spectrum of gamma rays in the decay of Cs-134 was studied with a newly installed Siegbahn-Slatis beta ray spectrometer using a strong source and thick lead and uranium radiators to bring out weak lines. Lines corresponding to the following gamma rays were found. Expressed in kev; 467, 553, 571, 607, 794, 1027, 1164, 1368, 1401.

((End of Abstract))

Figure 1 ((not shown)) shows the spectrum of the photoelectric conversion electrons of the gamma rays in lead of thickness 110 mg/ cm^2. Photoelectric lines were observed corresponding to the following gamma ray energies expressed in kev; 467 ± 15, 553 ± 7, 571 ± 7, 607 ± 5, 794 ± 3, 1027 ± 15, 1164 ± 10, 1368 ± 5, and 1401 ± 15. This confirms the gamma ray energies reported by Schmidt and Keister[**] and by Waggoner[***], et al, who studied the electron spectrum caused by internal conversion, and gives in addition 2 gamma rays, 1.47 Mev and the other at 1.40 Mev. A fairly consistent level scheme for barium can be drawn to explain most of the gamma ray transitions, though the gamma rays of energy 1.036 Mev has been attributed by some observers to an alternate K capture decay branch. The Radio Chemical Center, Amersham, England, which supplied the active cesium bromide gave us the quantitative spectrographic analysis of the material.
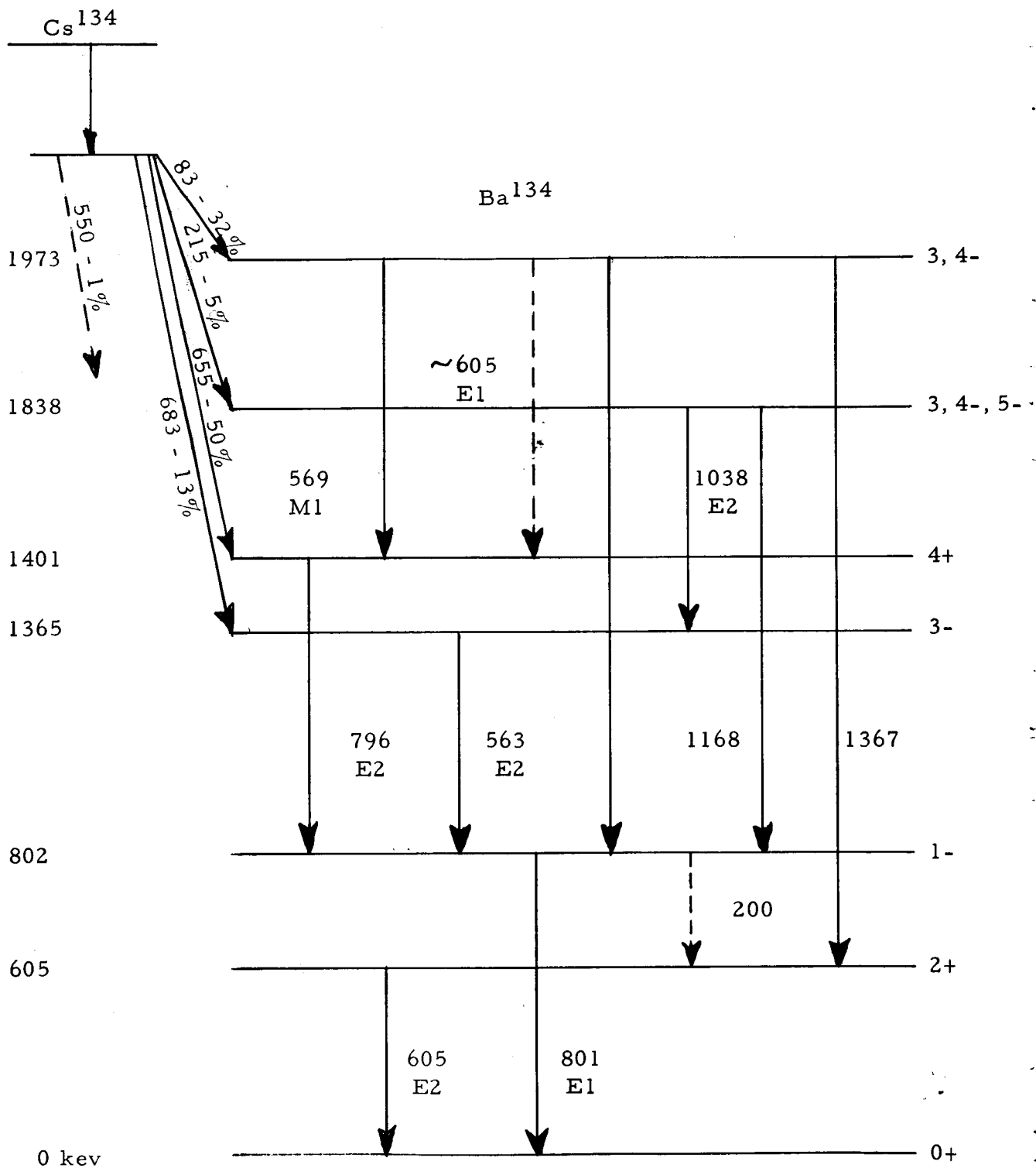
FIGURE Cs4-7.   DECAY SCHEME FOR Cs-134

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3.2.28A   THE NUCLEAR SPIN AND MAGNETIC MOMENTS OF Na-24, K-42 RB86, Cs-131, and Cs-134. R. H. Bellamy and K. F. Smith, Cavendish Laboratories, Cambridge, Philosophical Magazine 44, 33, 1953

3.2.29   DECAY OF CESIUM-134 AND THE LEVEL SCHEME OF BARIUM-134. P. N. Trehan, John D. French and Max Goodrich (Louisiana State University, Baton Rouge, Louisiana). Physical Review 131 2625-31, September 1953

<div align="center">ABSTRACT</div>

The energy (in kev) and the relative intensity of the gamma rays following the decay of Cs-134 have been measured as 475 (1.1), 563 (9), 569 (11), 605 (98), 800 (93), 1038 (1.1), 1168 (2.7), and 1367 (3.5). With the help of the various scintillation spectrometry techniques, no gamma rays of energy 960, 1570, 1640 1770 and 1970 kev reported earlier by certain workers could be detected. In addition to the already established 86 kev (26%) and 655 kev (71%) and point beta rays, three beta rays of end point and intensities 1453 kev (0.13%) 892 kev (0.7%) 410 kev (2.1%) were confirmed by careful measurements with the help of the beta ray spectrometer. The K-conversion coefficient of the gamma rays and the log ft value of the beta rays were obtained. The measurements established more firmly the decay scheme including the spin and parity assignments to the various levels.

((End of Abstract))

Source Preparation: The Cs-134 used in our experiments was obtained as cesium chloride in hydrochloric acid from Oak Ridge National Laboratory where it had been made by (n, gamma) reaction in Cs-133. The sources used for the beta ray and the internal conversion electron studies were mounted on thin films of collodion (about 5 - 10 micro-grams/cm^2 thickness). A drop of acid-free solution of active material was evaporated on a collodion film already treated with insulin. The sources used for the beta ray work were prepared by evaporation of a drop of active material either on aluminum foil backing or on lucite backing. (Figure 11, the decay scheme of Cs-134 is presented as Figure Cs4-8.)
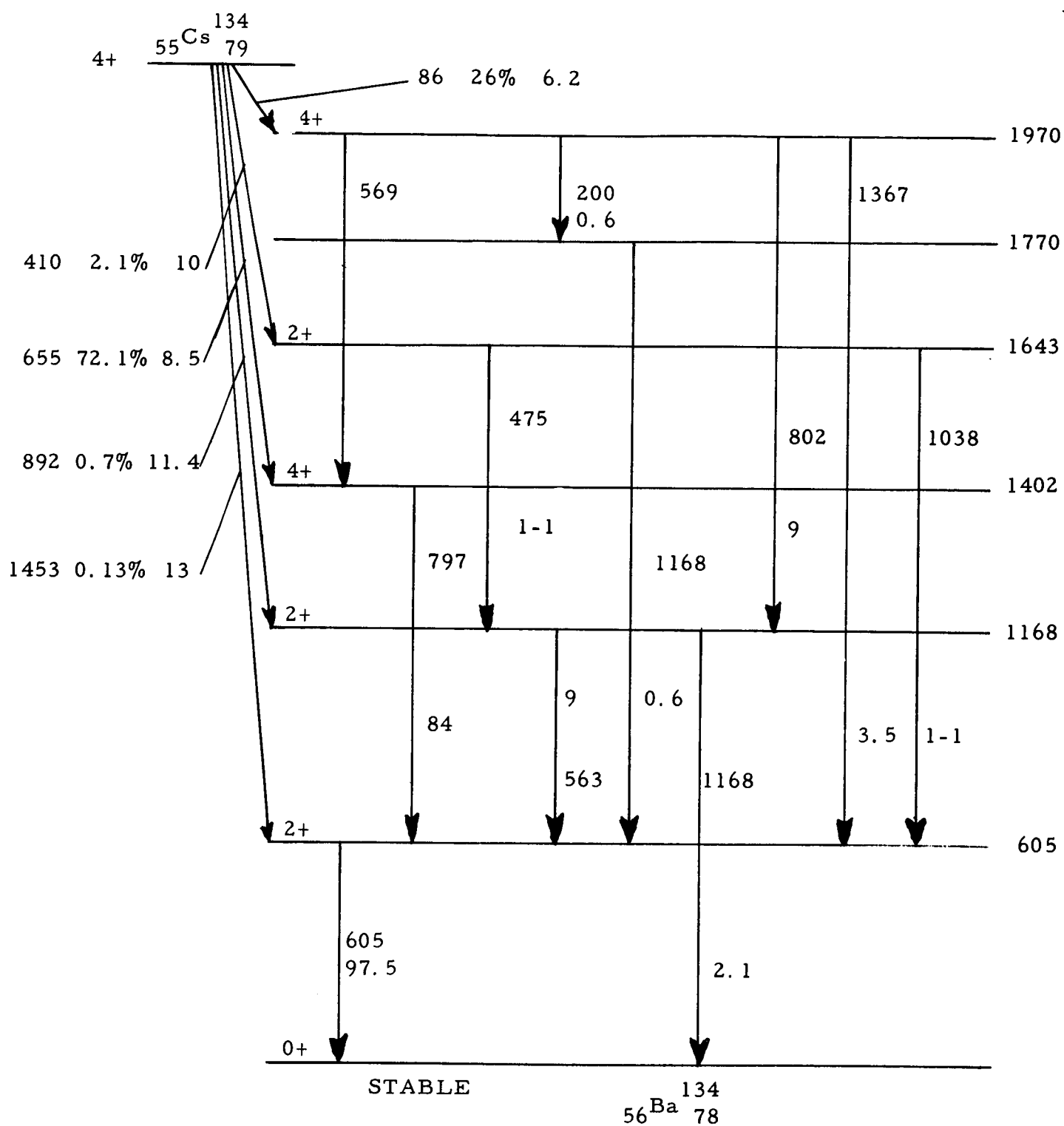
FIGURE Cs4-8.   DECAY SCHEME FOR Cs-134

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3.2.30   THE RADIOACTIVE DECAY OF CESIUM-134. OSMIUM-185, 191, 193.   J. M. Cork, J. M. LeBlanc, W. H. Nester, D. W. Martin and M. K. Brice (Department of Physics, University of Michigan, Ann Arbor, Michigan). Physical Review 90, 444-7, May 1953

PARTIAL ABSTRACT

From sources of cesium of high specific activity produced in the pile and studied in photographic magnetic spectrometers 19 electron conversion lines were observed.   These are interpreted to show the existence of 11 gamma rays, 4 of which have not been previously reported.   Certain K/L ratios are measured and the resolution of the components of the beta radiation presented.   The plausible decay scheme consisting of 7 levels in the resultant Ba-134 nucleus is offered ((balance of abstract referring to osmium has been omitted)).   A proposed decay scheme for Cs-134 is shown as Figure Cs4-9.

3.2.31   THE BETA-SPECTRUM OF 2.3 YEAR CESIUM-134. F. H. Schmidt, and G. L. Keister (University of Washington).   Physical Review 86, 632, 1952

The electron radiations resulting from the decay of Cs-134 have been studied in a high resolution solenoidal spectrometer.   Conversion electrons have been observed from seven gamma rays. 561.5 ± 1.0, 566.6 ± 0.8, 601.2 ± 0.5, 793.1 ± 0.7, 1037.2 ± 2.6, 1164.4 ± 2.9 and 1365.7 ± 3.3 kev.   The two lowest energy gammas whose ratio of K electron intensities is about 0.5, corresponds to the single gamma ray found by the other workers.   The 3 high energy lines are very weak: the measured K-L differences do not exclude conversion to xenon but indicate that conversion is more probably occurring in barium.   There is no evidence of a contaminent.   The continuous spectrum shows some indication of two high energy components whose end points differ by 30-40 kev.   The end point of the low energy branch (about 24%) is about 79 kev.   On the basis of these energies and other data a fairly consistent scheme for Ba-134 can be constructed with levels at 793, 1359, 1394, and 1955 kev.   The K internal conversion coefficients for the 793 and 601 gammas can be found with reasonable certainty.   (2.1 ± 0.2 and $5.7 \pm 0.5 \times 10^{-3}$, respectively.)   Coefficients for the 561 and 566 depend strongly upon which is associated with the low energy beta branch.   The role of the 1037 gamma is very uncertain.
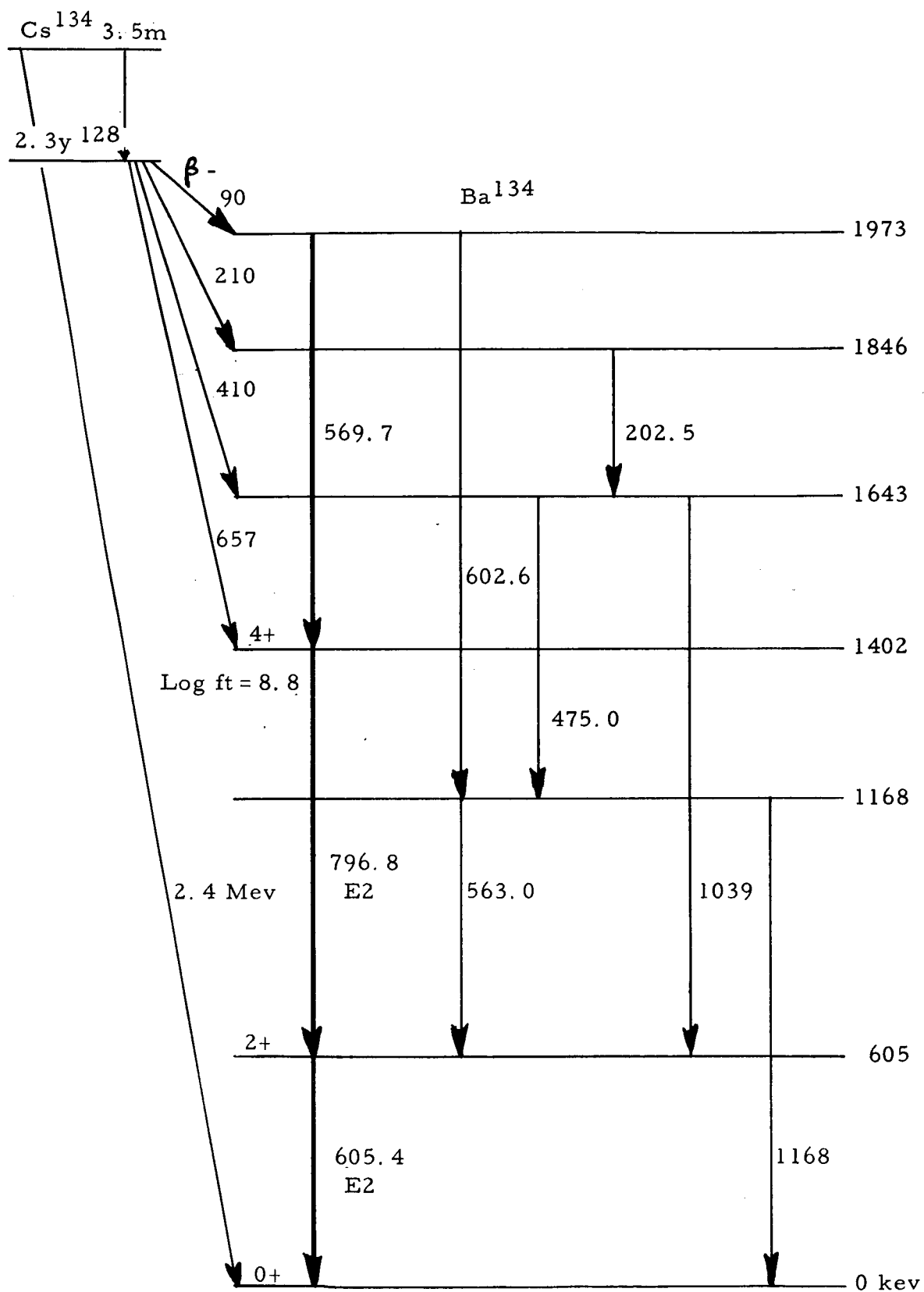
FIGURE Cs4-9. NUCLEAR LEVELS IN Ba-134 FOLLOWING BETA
EMISSION FROM Cs-134

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3. 2. 32   THE NUCLEAR SPIN AND MAGNETIC MOMENT OF
$_{55}$Cs-134.   V. Jaccarino, B. Bederson and H. H. Stroke
(Research Laboratory of Electronics, and Department of
Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts).   Physical Review 87, 676-7,
August 1952

The atomic beam magnetic resonance method has been applied to the
measurement of the hfs interaction in the ground state of the radio-
active nuclide Cs-134.   A 200-millicurie sample of $(Cs-134)_2CO_3$ was
prepared by neutron irradiation in the Brookhaven pile, yielding a
ratio of Cs-134 to Cs-133 of 1 to 6000 in the sample.   A directional
oven of special design was used to produce the atomic beam of cesium,
which after being ionized at the hot wire detector was analyzed with a
mass spectrometer having an enrichment factor of 2000 per mass
number at the mass 134 position.

3. 2. 33   ANGULAR CORRELATION OF THE GAMMA-RAYS OF
CESIUM-134.   Bertol L. Robinson and Leon Madansky
(John Hopkins University, Baltimore, Maryland).
Physical Review 84, 604, November 1951

A program has been initiated for the study of the correlations of
cascade radiations in the decay of radioisotopes.

3. 2. 34   GAMMA RAYS OF Cs-134.   V. S. Shpinel.   Zhur.
Eksptl'. i Teoret. Fiz. 21, No. 7, 853-5 (1951) July.
(Letter to the Editor; in Russian)

The gamma-ray spectrum of Cs-134 has been measured with a gamma-
ray spectrometer previously described by the author ((Shpinel, Zhur.
Tekh. Fiz. 20, 834 (1950); NSA 5-3725)).   The following gamma-ray
energies (in kev) were found, the figures in parentheses being relative
intensities: K_1, 569 ± 5 (0.35 ± 0.09); L_1, 571 ± 5; K_2, 601 ± 4 $(0.94$
$\pm 0.24)$; L_2, 601 ± 7; K_3, 794 ± 7 (1.0); L_3, 793 ± 7; K_4, 1024 ± 10,
K_5, 1110 ± 10; and K_6, 1347 ± 14 (0.017 ± 0.008).

3. 2. 35   INTERNAL CONVERSION OF GAMMA RAYS FROM
COBALT-60, CESIUM-134, AND ZINC-156.   M. A.
Waggoner, M. L. Moon, and A. Roberts (Department
of Physics, State University of Iowa, Iowa City, Iowa).
Physical Review 80, 420-8, November 1950.

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Using a double coil thin lens magnetic beta ray spectrometer of
transmission 2 40% and line width of approximately 3% the internal
conversion coefficients of the gamma rays of Co-60, Cs-134 and
Zn-65 have been measured.   Sufficient precision has been obtained in
several cases to verify the theoretical values and to obtain unambiguous
identification of the multipole character of the gamma rays.   Internal
conversion coefficients as small as 10^{-5} can be measured with a
precision of 5% ((5% error)) or better.   The results obtained indicate
that both of the gamma rays from the Co-60 are electric quadrupole
(EQ), the 560 kev gamma rays from Cs-134 is either EQ or MD or a
mixture of these.   The 602 and 799 kev gamma rays from Cs-134 are
both EQ, the 1.114 Mev gamma ray from Zn-65 is either EQ or MD or
a mixture of these, and the 1.363 Mev gamma ray from Cs-134 may be
EQ   Further data on the decay scheme of Cs-134 are given.   The
results show that in combination with angular correlation measure-
ment, internal conversion data determined the angular momenta and
parities of the excited nuclear states   ((Figure 5 of this article,
tentative decay scheme for Cs-134, is shown as Figure Cs4-10.))

3 2.36   CROSS-OVER TRANSITIONS Ir-194, Ag-110, and Cs-134
            Richard Wilson (Clarendon Laboratory, Oxford, England).
            Physical Review 79, 1004, September 1950.

According to the accepted decay schemes for these isotopes, cross-
over transitions might be expected.   A search has been made for
these transitions using the photodisintegration of beryllium and
deuterium as threshold detectors for a high energy gamma energy
radiation   The photoneutrons were detected by Szilard-Chalmers
reaction in ethyl iodide under conditions in which the detection
efficiency has been measured as a function of energy.   Approximate
estimates of the intensities have been made using pile activation data
to get the disintegration rate of the isotope.   The accuracy of these is
about 50%.   The results are shown in Table 1.   ((Table 1 is entitled
Cross-Over Transition Data and is shown in part as follows.))
Isotope; Expected energy (Mev) 1.96; expected intensity in photons
per disintegration, 10^{-5}; observed intensity photons per disintegrations,
less than 10^{-4}.   For Cs-134 the upper limit to the intensity is in good
agreement with the results of Fluharty which had escaped notice until
the experiment had been completed.

3.2.37   GAMMA-GAMMA-CORRELATION EXPERIMENTS. J. R.
            Beyster and M. L. Wiedenbeck.   Physical Review 79,
            411, July 1950

$_{54}Xe^{134}$ $_{54}Cs^{134}$ $_{54}Ba^{134}$

β - 90±10 kev

γ

γ

5.60
±.005
Mev

0.631
+.013
-0.017

β-

4+

3+
or
4+

γ
1.363
±.005
Mev

1.037
and
1.170
Mev
gammas

γ
0.799
±0.003
Mev

2+

γ
0.602
±.004
Mev

0+
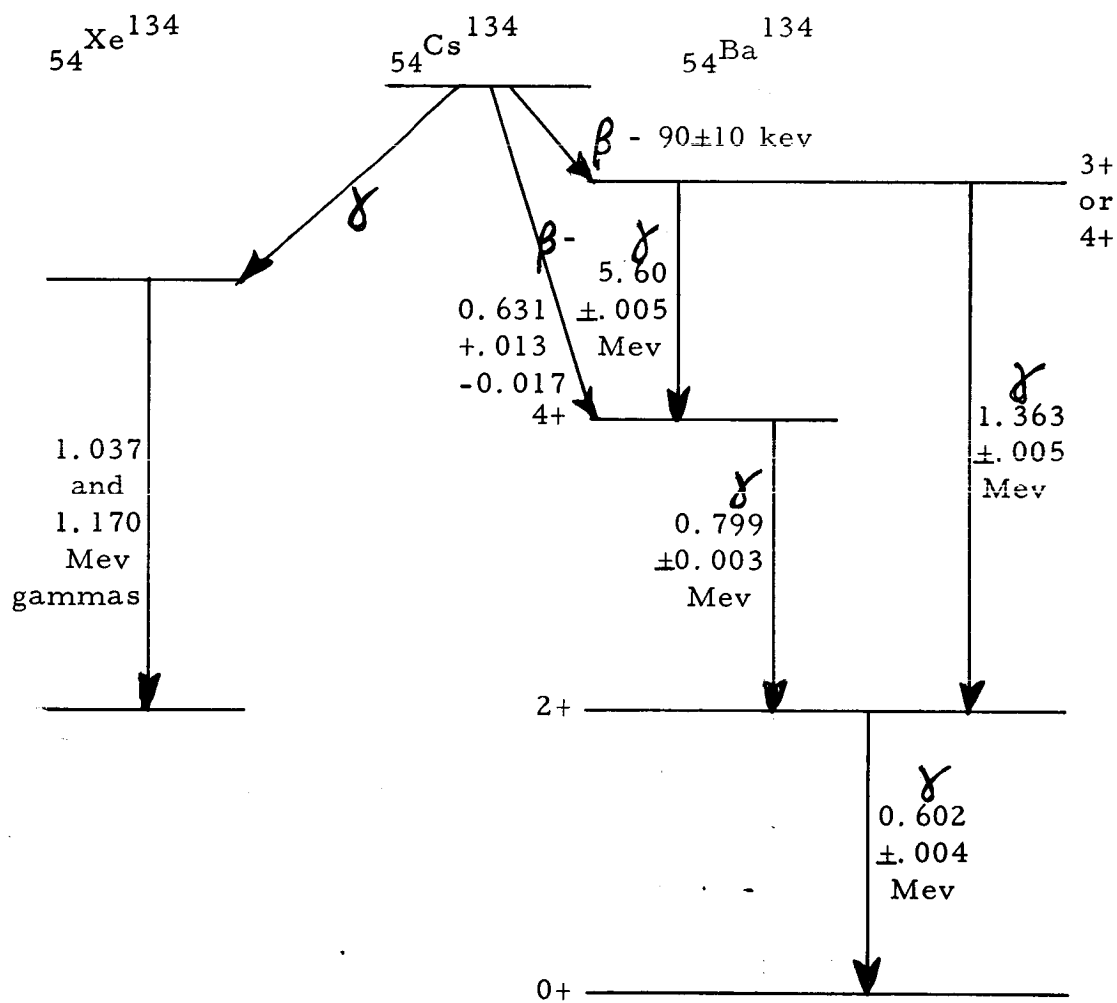
FIGURE Cs4-10.   TENTATIVE DECAY SCHEME OF Cs-134

ABSTRACT

The correlation of successive gamma rays has been reported
previously for a number of radioactive substances. We have also
investigated the gamma-gamma correlation for several of those
activities and for a few other isotopes. Figure 1, Curve B ((not
shown)) is observed function for Cs-134. It will be recalled that
Cs-134 has essentially three gamma rays in cascade, the upper gamma
appearing about 25% of the time. It is possible to explain the
experimental data with the assumptions that the two lower transitions
are quadrupole between states possessing angular momenta (J = 4, 2,
0) and that the upper transition is quadrupole with J = 4, 5, or 6 for
the uppermost state. The polarization correlation experiments and
the measurements of the total absolute conversion coefficient for Cs-
134 indicate that one of the lower transitions may be magnetic quad-
rupole ((Figure 1, not shown, presents gamma-gamma correlation
function of Co-60, Cs-134, and Ag-110)).

3.2.38   CORRELATION IN THE DIRECTION AND POLARIZATION
OF TWO SUCCESSIVE QUANTA FOR Rh-106, Co-60, and
Cs-134. A. H. Williams and W. L. Wiedenbeck (Randall
Laboratory of Physics, University of Michigan, Ann Arbor,
Michigan). Physical Review 78, 822, June 1950

ABSTRACT

Deutsch and Metzger have reported their observation of the correlation
between the polarization of one quantum in the direction of emission of
the other for the two successive gamma rays of Ph-106. We have used
a polarimeter of a type similar to that described by Deutsch and have
verified their results. In the case of Cs-134 no polarization
correlation was observed. According to the theory, correlation
should be found for two quadrupole transitions, one of which is
magnetic and the other electric, only if the experimental arrangement
is such that one can distinguish between which of the two quanta goes
to the polarimeter or to the individual counter. In our case, this
discrimination was not possible. If both transitions are electric or
both magnetic, this discrimination is not necessary in order to observe
a correlation. If one assumes then that both transitions are quad-
rupole the conclusion is that one is electric and the other is magnetic.

3.2.39   THE INTERNAL CONVERSION ELECTRONS OF SEVERAL
SHORT-LIVED NEUTRON INDUCED RADIOACTIVITIES.
Richard L. Caldwell (University of Missouri, Columbia,
Missouri, and Argonne National Laboratories, Chicago,
Illinois). Physical Review 78, 407-11, May 1950

ABSTRACT

Accurate values of transition energies were measured for seven neutron induced radioactivities using a permanent magnet beta ray spectrograph. A special vacuum gate permitted the introduction of short-lived samples within 12 seconds after the end of bombardment without disturbing the vacuum in the spectrograph. Transition energies accurate to about 1% were determined as follows: Cesium (3 hours), 128.0 kev; Cobalt (10.7 minutes), 58.9 kev; Columbium (6.6 minutes), 41.5 kev; Dysprosium (1.3 minutes), 109.0 kev; Dysprosium (2.6 hours), 87.8 kev; Iridium (1.5 minutes), 54.7 kev; Thulium (120 days), 84.4 kev. For the five isomeric transitions approximate values of the relative intensities of the electron lines were determined, and an assignment was made of the multipole outlet of the radiation, assuming electric multiple radiation. ((The following is a partial presentation of Table 1. The balance of Table 1 deals with Cobalt, Dysprosium, and Columbium and is not presented.))

TABLE 1. ELECTRON AND TRANSITION ENERGIES

Element	Half Life (hours)	Hp (Gauss-Cm)	Electron Energy (kev)	Conversion Shell	Transition Energy (kev)
Cs*	3	1067.5	92.0	K	128.0
		1251.1	123.0	L	128.0
		1273.5	127.0	M	128.0

3.2.40   COINCIDENCE AND ABSORPTION MEASUREMENTS ON CESIUM-134, IODINE-124, GOLD-199, AND CALCIUM-43. J. Lawrence Meem, Jr., and Fred Maienschein (Physics Department, Indiana University, Bloomington, Indiana). Physical Review 76, 328-32, August 1949

PARTIAL ABSTRACT

The beta ray spectrum of Cs-134 was investigated by absorption and beta-gamma coincidence measurements. Beta rays of 0.60 Mev and about 90 kev were observed. ((The rest of the abstract is concerned with the other isotopes and is not reproduced.))

((End of Abstract))

The disintegration scheme of Cs-134 has been investigated by Elliot and Bell**, and by Siegbahn and Deutsch*** using spectrometer and coincidence techniques. The spectrum of Cs-134 has been investigated ((by the authors of this article)) by absorption and beta-gamma coincidence methods. The source was obtained from Oak Ridge and was purified by an amberlite resin ion exchange column at this University. The results are in complete agreement with the disintegration scheme proposed by Elliot and Bell**.

**Phys. Rev. 72, 979, 1947
***Phys. Rev. 71, 483, 1947

3.2.41 AECU-517 (UAC-71) nd. 1 page). TRANSITION ENERGY OF SOME NUCLEAR ISOMERS. R. L. Caldwell, E. der Mateosian, and M. Goldhaber

Accurate values of the transition energy have been measured for a number of isomers using a permanent magnet beta ray spectrograph similar to that described by Hill in Physical Review 74, 78, 1948. As special vacuum gage permits the introduction of short-lived samples. Some results are summarized in the following table: ((table reproduced in part)) Isomer; Cesium-134; half-life, 3 hours; shells from which electrons have been observed, K, L, M; transition energy 128.0 ± 0.5.

3.2.42 THE DISINTEGRATION SCHEME OF CESIUM-134. Kai Siegbahn (Nobel Institute for Physics, Academy of Science, Stockholm). Physical Review 73, 410, February 1948

ABSTRACT

Elliot and Bell have recently published a disintegration scheme for Cs-134 which is more complete than the one proposed originally by the present authors. Some time ago we obtained results very similar to those of Elliot and Bell** and we confirmed their disintegration scheme in every detail. (As a result of calculations, the fraction of disintegrations leading to the 1.97 Mev level in barium is 0.26 ± 0.08 in excellent agreement with the values posed by Elliot and Bell)) From absorption measurements using a windowless counter, we estimate the abundance of the very soft beta ray spectrum at 0.32 ± 0.08. Our best values for the gamma ray energies are now 0.566 ± 0.01 Mev, 0.603 ± 0.01 Mev, and 0.798 ± 0.15 Mev based on the photoelectron energies from a thin uranium radiator.

**Phys. Rev. 72, 979, 1947

3.2.43   DISINTEGRATION SCHEME OF 1.7-YEAR CESIUM-134.
L. G. Elliot and R. E. Bell (Division of Atomic Energy,
National Research Counsel of Canada, Chalk River,
Ontario).   Physical Review 72, 979, 1947

ABSTRACT

The disintegration of the long-lived isomer of Cs-134 has been studied
with a short magnetic lens beta ray spectrometer together with coinci-
dence techniques.   The shape of the beta ray spectrum was studied
down to the low energy cut-off of the counter window (about 0.015 Mev)
by use of a source of thickness approximately 0.1 mg/cm^2 mounted on
a mica backing about 1.0 mg/cm^2.   A Fermi plot of this spectrum
using the exact Fermi function of (Z, N) for Z = 55 is shown in Figure
1 ((not shown)).   The secondary electron spectrum obtained by photo-
electric conversion of the gamma rays in a thin 17 mg/cm^2 lead
radiator is shown in Figure 2 ((not shown)).   Three gamma rays are
observed whose energies are respectively 0.568 ± 0.015, $0.602 \pm$
0.015, and 0.794 ± 0.015 Mev with intensities of 0.26, 1.0, and 1.0,
respectively, after allowing for the energy variation of the photo-
electric cross section.   These results are consistent with the dis-
integration scheme proposed in Figure 3.   ((Figure 3 is shown as
Figure Cs4-11.))

3.2.44   THE DECAY SCHEME OF CESIUM-134.   Kai Siegbahn
and Martin Deutsch, Massachusetts Institute of
Technology, Physical Review 71, 483, 1947

ABSTRACT

The long lived isomer of Cs-134 has been studied by magnetic
spectrometer and coincidence techniques with a view to its use as a
radioactive standard.   The great majority of the disintegrations,
about 95%, proceed by the emission of beta particles of (0.645 ± 0.02)
Mev maximum energy to an excited state of Ba-134 with (1.36 ± 0.03)
Mev excitation energy, followed by the successive emission of new
gamma rays of (0.584 ± 0.012) Mev and (0.776 ± 0.015) Mev,
respectively.   In a few per cent of the disintegrations a gamma ray
of (1.35 ± 0.03) Mev is emitted.   This is probably due to single
quantum de-excitation of the same excited state.
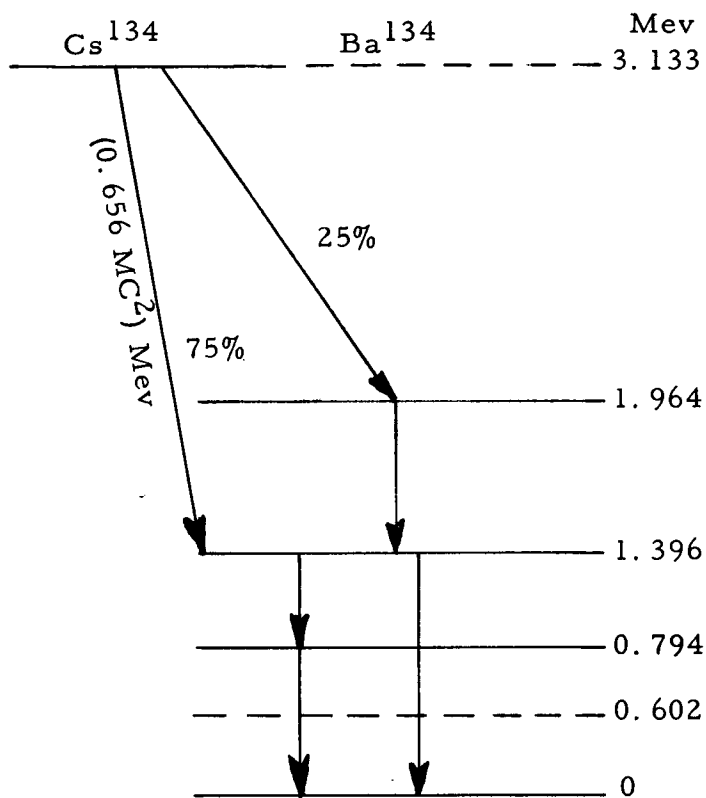
FIGURE Cs4-11.   PROPOSED DISINTEGRATION SCHEME
                 FOR Cs-134

3.3 CESIUM-137

HALF LIFE

Cs-137 30.0 ± 0.38 years.   Ref. 38 Cs-134
Analytical Chemistry 7, 797-99, June 1963

Ba-137 158 ± 5 seconds.   Ref. Phys. Rev. 75, 197
Jan. 1949

ENERGY LEVELS AND DECAY SCHEME

Cs-137   <u>93.5%</u>* Ba-137m $Beta_{max} = 0.514 \pm 2$ Mev

+   Gamma $= 0.66$

Cs-137   <u>6.5%</u>* Ba-137 $Beta_{max} = 1.175$ Mev

**Cs-137
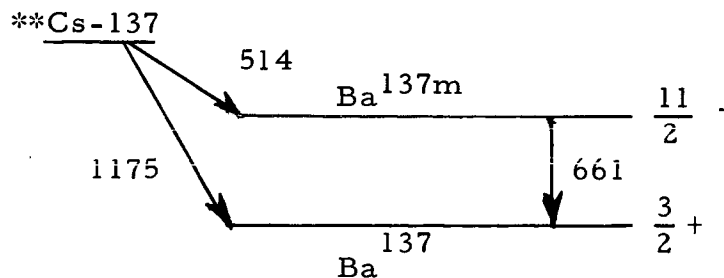
α_K $= 0.11 \pm 0.01$)
)
$\alpha_K/\alpha_L = 6.0 \pm 0.1$) Ref. 38 Izvestia Akad Nauk
)   SSSR 12, 19, 324-37
$\alpha_K/\alpha_M = 4.1 \pm 0.4$)   May-June 1955

**Ref. 3.3.24 Nucl. Phys., 5, 122-140, Jan. 1958
***Ref. 3.3.11 Z. Physik 168, 292-7, 1962

3.3.1   ISOTOPIC POWER DATA SHEETS, Compiled by S. J.
         Rimshaw, Oak Ridge National Laboratory, Oak Ridge,
         Tennessee.   For presentation at Industry Information
         Meeting on Isotopic Power Development and Applications,
         Washington, D. C., May 18-19, 1964

Cs-137 Glass

Source Material	Cesium borosilicate glass
Half-Life	Cs-137 - 30 ± 0.3 years (Ba-137m - 2.6 min)

Decay and Radiation
   Properties

$$Cs\text{-}137 \longrightarrow Ba\text{-}137m$$

Beta - Cs-137	Gamma	Other
0.51 (92%)	none	none
1.17 (8%)		

Beta - Ba-137m	Gamma - ba-137m	
none	0.662	IT

Isotopic Composition	43.4% Cs-133, 20.1% Cs-135, and 36.5% Cs-137
Activity Concentration	16 curies/g of glass
Radiochemical Purity	> 95%. The only significant radiochemical impurity is Cs-134. The amount of Cs-134 in the Cs-137 product will vary according to the age of the waste being processed; it may be as much as 5% of the Cs-137 activity but in currently available feed material is < 3%.
Chemical Purity	> 98% cesium, < 2% Rb, small quantities of Na, K, SiO_2 introduced in reagents
Specific Power	0.0774 watts per gram of glass or 4.84 watts/kilocurie
Thermal Energy	207 curies per thermal watt
Density	3.1 g/cm^3

Power Density	0.24 watts/cm^3 based on 16 curies/g of glass
Thermal Conductivity	Estimated to be $1\text{-}2 \times 10^{-3}$ cal/sec·cm·°C at room temperature and $2.5\text{-}3 \times 10^{-3}$ cal/sec·cm·°C between 1000°C and 2000°C by analogy to sodium borosilicate glasses
Coefficient of Expansion	Estimated to be $1\text{-}2 \times 10^{-5}$ °C^{-1} (a factor of ~ 4 less than ordinary glass)
Softening Point	~ 1275°C
Mechanical Strength	The Cs-137 glass has exhibited brittleness. No definitive measurements of mechanical strength have been made
Thermal and Radiation Stability	The glass devitrifies if held at 1000°C for a few hours

Radiation Attenuation

Dose Rate, rads/hr at 100 cm	Shielding in Centimeters of Uranium Required for a Cs-137 Source Strength of (Source contains 1% Cs-134 and 99% Cs-137)		
	100 w	1000 w	10,000 w
100	1.5	3.4	4.7
10	3.6	5.5	7.2
1	6.0	8.1	9.8
0.1	8.4	10.8	12.6

Gas Evolution Due to Radioactive Decay Processes	None
Leach Rate	~ 0.2 mg/cm^2·day in H$_2$O at 30°C
Vapor Pressure	Volatility of Cs at 1200°C is 3.5 mg/cm^2·hr (~ 12 mc of Cs-137/cm^2·hr)
Resistance to Thermal Shock	Poor

| Burnup Characteristics | Does not oxidize; has ablative characteristics of glass |
| Capsule Compatibility | Excellent with usual capsule materials such as stainless steel and Hastelloy "C". |

3.3.2 +GAMMA-RAY ANGULAR CORRELATION ATTENUATION FACTORS. B. Herskind and Y. Yoshizawa (Universitet, Copenhagen). Nucl. Instr. Methods, 27: 104-8 (Apr. 1964)

Gamma attenuation factors for angular correlations and angular distributions were computed from total absorption coefficients for a 76 x 76 mm NaI(Tl) cyrstal. The calculations cover the range of distances between a source and a crystal surface from 1 to 20 cm and the range of energies from 0.05 to 4.0 Mev. In order to determine attenuation factors for the photopeak alone, measurements were performed for gamma rays of 0.060 Mev (Am-241), 0.142 Mev (Ce-141), 0.32 Mev (Cr-51), 0.662 Mev (Cs-137), 1.332 Mev (Co-60), and 2.754 Mev (Na-24) within the same range of distances. The attenuation factors for the photopeak were computed by using the experimental results. The experimental factors are compared to the results calculated from the total absorption coefficients and to the results of the Monte Carlo calculation given by Yates.

3.3.3 *IN-TIME INTEGRATED FISSION RATE STUDIES IN URANIUM USING ALPHA OR GAMMA SPECTROMETRY. A. Guillon, S. May, S. Sapena, and R. Sauvagnac. Bull. Inform. Sci. Tech. (Paris), No. 81, 35-7 (Mar. 1964) (In French)

Some methods for measuring burn-up of fissile material are reviewed. Alpha spectrometry after irradiation (measurement of U-235 disappearing), which is accurate only for high integrated fluxes, is discussed. Measurements of the ratio of fission products to uranium are also considered. Some examples are given for irradiations made under different conditions. The fission products studied were Cs-137, Ce-144, and Ba-140. A chemical separation is described for each of these radionuclides.

3.3.4 *THE STRUCTURE OF THE GAMMA-FIELD OF A CESIUM-137 SOURCE. V. A. Vorob'ev. At. Energ. USSR, 16:69-70 Jan. 1964. (In Russian)

The angular spectrum function of scattered gamma radiation from an infinite, isotropic plane Cs-137 source, having an $E_0 = 0.661$ Mev in an air-equivalent medium, was investigated by the Monte Carlo method at distances corresponding to 0.5, 1, and 2 mean free paths (MFP) from it. The surface activity was assumed to be 1 quantum/cm^2 sec. At 0.5 MFP from the source the chief contribution of the scattered radiation was noted at a body angle of about 75°; at 1 MFP the maximum was located at 60°; and at 2 MFP it was found at 0°. At the shortest distance, carrying out the observations under 0°, in the direction of normal, a peak was noted at the 0.3 Mev region in the energy spectrum; this was due to the first-generation gamma quanta emitted at about 70°. The integrated spectrum of the plane source was similar to the integrated spectra of point sources in a homogeneous medium. The buildup factors calculated agreed well with the values reported by H. Goldstein.

3.3.5   *IRRADIATION SOURCES FOR THE NON-DESTRUCTIVE TESTING OF METALS.   E. Becker, Technik (Berlin), 18: 793-9 (Dec. 1963).   (Rev. Metal Lit., 21; No. 5, Mar. 1964)   (In German)

Physical properties of common irradiation sources used in the testing of metals, such as Co-60, Cs-137, Ir-192, and Tm-170 isotopes, and their application in the testing of steel were investigated. The defect detectability was determined and optimum wall thickness ranges for the individual isotopes were investigated.

3.3.6   *CALCULATION OF THE SPECTRAL-ANGULAR DISTRIBUTION OF SCATTERED GAMMA QUANTA FROM A MONODIRECTIONAL CESIUM-137 SOURCE IN IRON. L. P. Kimel', A. M. Panchenko, and V. P. Terrent'ev. At. Energ. USSR, 15:328-31 (Oct. 1963) (In Russian)

The Monte Carlo method was used for calculating the spectral and angular distribution of the scattered energy of gamma quanta, emitted with an initial energy of 0.661 Mev by a Cs-137 point source placed in an infinite Fe medium. The 5420 measurements were carried out by determining the path of the quanta up to the first interaction, determining the type of the interaction, and calculating the energy of the scattered gamma quantum by the Compton effect; at the same time the direction of the flight path after scattering was also determined. The measurements were repeated until the quantum disappeared as the result of the photoeffect or because of transition to an energy level

below 10 kev. Angular integration of the scattered radiation spectra showed that the energy of the quanta is limited within 0.13 to 0.26 Mev. The data obtained made it possible to calculate the buildup factor B_E of a flat, monodirectional source.

3.3.7   Refer to 3.2.8. HALF LIVES OF CESIUM-137 AND CESIUM-134 AS MEASURED BY MASS SPECTROSCOPY. Anal. Chem. 7, 797-99, June 1963

3.3.8   *THE SHAPES OF THE SCINTILLATION GAMMA-RAY SPECTRA AND MEASURING CONDITIONS. Shinji Okano (Inst. of Physical and Chemical Research, Tokyo). Radioisotopes (Tokyo), 12: 261-5 (May 1963) (In Japanese)

Scintillation gamma-ray spectra of various nuclides are examined. It is shown that the shapes of the spectra are varied, even for the same nuclide, by the geometries and dimensions of the gamma-ray sources and the phosphors and their relative positions. Phosphors of NaI(Tl) with varying geometries are used. The gamma-ray sources examined are Na-22, Mn-54, Co-60, Zn-65, and Cs-137. The counts vs wave-height curves are shown. (From NSA of Japan)

3.3.9   *MASS-SPECTROMETRIC DETERMINATION OF MICRO-QUANTITIES OF CESIUM. I. V. Burovina, V. P. Nesterov, and D. G. Fleishman. Radiokhimiya, 5:272-6 (1963) (In Russian)

Mass-spectrometric method was used for determining Cs-133 in biological objects. The half-life of Cs-137 was determined as 30.1 ± 0.7 years. Data are given on Cs-133 content in a human brain and muscle.

3.3.10   THE MASS SPECTROMETRIC DETERMINATION OF THE CESIUM-137 HALF LIFE. B. F. Rider, J. P. Peterson, Jr., and C. P. Ruiz. (General Electric Company, Atomic Power Equipment Department, Vallecitos Atomic Laboratory, Pleasanton, California). Nuclear Science and Engineering 15, 284-7 March 1963

ABSTRACT

The half life of Cs-137 has been measured by observing the rate of growth of stable Ba-137 from a known quantity of Cs-137 by the use

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of isotope dilution mass spectrometry. The half life thus obtained is 29.2 ± 0.3 years.

((End of Abstract))

Sample preparation. A 200 millicurie batch of fission product Cs-137 in 5 milliliters of one mole HCL was passed through a Dowex 50 column. The column was washed with an additional 15 milliliters of one mole HCL. A small fraction of this eluate was mass analyzed and the remainder was added to a polyethylene bottle containing accurately weighed amounts of standardized Cs-133 and enriched Ba-138 solution. A number of Cs-137 atoms in this master solution was determined to be a standard deviation of 0.68% from 183 mass scans from ten filaments. (The value of 29.2 ± 0.3 years is different to a small extent from a previous determination by mass spectrometry**.) The difference from the previous mass spectrometric value can be accounted for primarily by a difference in the measurement of the slope of the Ba-137 growth line. In this work this slope was obtained with improved accuracy by making many observations over a longer period of time, and by eliminating the need for chemical loss correction.

**Farrar, et al, Canadian Journal of Chemistry, 39 page 681, March 1961.

3.3.11   *THE BETA SPECTRUM OF Cs-137.   H. Daniel and H. Schmitt (Max-Planck-Instut fur Kernphysik, Heidelberg). Z. Physik, 168: 292-7 (1962)   (In German)

The beta spectrum of Cs-137 was measured with an iron-free spectrometer. The energy of the soft component was found to be E_0 = 514 ± 2 kev.   The parameter k of the hard component shape factor $C_{2VA}^{(2)}$ (W) = $q^2 + kp^2$ was determined to be k = 0.015 ± 0.004. The beta intensities amount to 6.5% (hard component) and 93.5% (soft component).   The K conversion coefficient of the isomeric transition was measured to be α_k = 0.093 ± 0.003, in excellent agreement with Sliv's theoretical value.

3.3.12   THE HALF-LIFE OF CESIUM-137.   D. G. Fleishman, I. V. Burovina, and V. P. Nesterov, Atomanya Energiya, Vol. 13, No. 6, 592-3, December 1962

ABSTRACT

The half life of a radioactive isotope can be determined by various approaches, by measuring the absolute activity of a known number of

its atoms in terms of the decrease in the amount of the radioisotope under study as time progresses, or in terms of the rate of accumulation of radioactive daughters. In the present note, the rate of decay of the Cs-137 in the sample is reported as a result of measuring the beta activity in a liquid scintillator in the amount of Cs-137 as found by the isotope dilution method. To measure the beta activity, a certain quantity of an aqueous solution of Cs-137 nitrate was introduced into a liquid scintillator. Approximately 0.3 milliliters standard solution was added to the scintillator constituting in total 1.5 of the total volume of the scintillator and depressing its light yield only negligibly. The fairly high light yield of the scintillator and the use of the FEU-1B photomultiplier tube, with excellent integrated sensitivity and a low tube noise level, made possible an efficiency of the order of 93% in recording Cs-137 betas.

((End of Abstract))

The value of the half-life of Cs-137 found from the above data is 30.1 ± 0.7 years. This value agrees within the limits of the error with the results reported by other authors in the recent literature (29 ± 1 year**, 30.4 ± 0.4 years***).

**Atomnaya Energiya, Vol. 10, No. 6, 622-3, June 1961
***Canadian Journal Chemistry 39, 681-3, March 1961

3.3.13   HALF LIFE OF CESIUM-137. B. F. Rider, J. P.
          Peterson, Jr. , and C. P. Ruiz (GE-APED, Pleasanton).
          Transactions of the American Nuclear Society 5, 1, 195-6
          June 1962

The half-life of Cs-137 has been determined from the rate of formation of daughter Ba-137 in a measured amount of Cs-137 by isotopic dilution mass spectrometry. Only one such measurement; 30.4 ± 0.4 years has been reported**. Other measurements based on radioactivity measurements include 26.6 ± 0.4, 30.0 ± 0.4, 28.6, 28.4 ± 1.4, 32.6 ± 1.6, 27, and 29 ± 1 year. Because of the uncertainty of this value and its importance in nuclear fuel burn-up analysis by the Cs-137 to uranium ratio method a re-investigation was undertaken using the mass spectrometer method. The Cs-133 solution was a primary standard prepared by weight from spectrographically pure CsCl. The Ba-138 was standardized by isotopic dilution with a primary standard prepared by weight from spectrographically pure CsCl. The Ba-138 was standardized by isotopic dilution with a primary standard prepared

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by weight from analyzed CP natural $BaCl_2 \cdot 2H_2O$. By isotopic dilution the initial number of Cs-137 and Ba-138 atoms in the flask were known to a standard deviation of 0.56% and 0.43%, respectively. Two solid emission mass spectrometers and a two-stage magnetic analyzer using an electron multiplier detector and pulse counting technique and a single stage magnetic analyzer with a Faraday caged detector and vibrating reed electrometer were used to determine the mass ratios.

((From this experiment)) the half life was determined to be 29.15 ± 0.25 years at one standard deviation. This value is consistent with the average of the values referenced and has a smaller uncertainty than previous measurements.

**Canadian Journal Chemistry 39, 681-3. March 1961.

3.3.14   MEASUREMENTS OF INTERNAL CONVERSION COEFFICIENTS. Solve Hultberg, Daniel J. Horen, and Jack M. Hollander (Lawrence Radiation Laboratory, University of California, Berkeley, California). Nuclear Physics, 28, 471-7. 1961

ABSTRACT

Internal conversion coefficients of M1, M4, and E2, transitions from the Y-87, Cs-137, Au-198, Ir-192, decays have been studied by using the internal-external conversion (IEC) method. For unhindered transitions of the 2+ $\longrightarrow$ 0+ type we have found $(Alpha_2)_{317} = 0.054 \pm 0.003$ for the 317 kev transition from Ir-192 and $(Alpha_2)_{412} = 0.028 \pm 0.0015$ for the 412 kev transition from Au-198, the theoretical values being 0.054 and 0.030, respectively.

3.3.15   ANALYSIS OF GAMMA RAY SCINTILLATION SPECTRA BY THE METHOD OF LEAST SQUARES. L. Salmon (Physics Division, UKAEA Research Group, Atomic Energy Research Establishment, Harwell, Didcot, Berks). Nuclear Instruments and Methods 14, 193-199, December 1961

ABSTRACT

The method of least squares has been applied to the analysis of gamma ray scintillation spectra, the calculations being performed on

a Ferranti "Mercury" computer. The method is superior to the usual graphical methods of quantitative interpretation. Analytical results are obtained rapidly, the accuracy being consistent with calculated precision. The method is particularly suitable for routine analysis at low counting rates.

3.3.16   DECAY HALF-LIFE OF CESIUM-137. M. P. Glazunov,
          A. I. Grivkova, B. A. Zaitsev, and V. A. Kiseley,
          Atomnaya, Energiya, Vol. 10, No. 6, 622-3, June 1961

The Cs-137 precipitation used in the present study was separated from a solution of uranium fission products by the ferro-cyanide method which is based on the ability of cesium to enter into a highly insoluble compound with nickel ferro-cyanide. The separated preparation was a solution of cesium chloride. An assessment of the radio chemical purity of the cesium shows that gamma-radiation due to radioactive impurities was less than 0.01% of the total activity. This was affirmed by mass spectrometric and beta-gamma spectrometric techniques. ((The value for the decay life of Cs-137 was determined by these authors to be 29 ± 1 year.))

3.3.17   CESIUM-137 AND ITS GAMMA-RADIATIONS IN TELE-
          RADIO THERAPY. R. Thoraeus, Acta-Radiologica, 55,
          385-95, May 1961

ABSTRACT

A review of the characteristics of cesium radioactivity including partial comparison with that of cobalt is given. The measurement of cesium gamma-radiation by means of an extensively calibrated sub-standard is described and the experimental results particularly the half-value layers of some materials are presented. Certain clinically important properties of the radiation, the radiation protection using radioactive cesium, and the result of determination of the peak energy of the roentgen radiation equivalent in penetration to the cesium gamma-radiation are discussed.

3.3.18   HALF-LIFE OF CESIUM-137. H. Farrar, A. K.
          Dasgupta and R. H. Tomlinson. Canadian Journal of
          Chemistry 39, 681-3, March 1961

ABSTRACT

The half-life of Cs-137 was found to be 30.4 ± 0.4 years by determining the amount Ba-137 produced in various times from a known

number Cs-137 atoms.   The number of barium and cesium atoms
were determined from isotope dilution data obtained with a mass
spectrometer.

((End of Abstract))

About 0.5 milligrams of fission product cesium was used for this
experiment amounting to about 20 millicuries of activity in generating
about 1×10^{-8} grams of Ba-137 per day.   Measurements of the
amount of Ba-137 formed in 8 different periods have been made.   The
period in each case was the time between similar parts of consecutive
cesium elutions.   From these data ((contained in the article)) the half-
life was calculated to be 30. 4 $\pm$ 0. 4 years.   The errors in the half-life
has been estimated from the assigned errors in each of the measured
quantities.

3.3.19   A LARGE VOLUME FOUR PI LIQUID SCINTILLATION
           DETECTOR.   B. G. Dunavant and J. E. Christian
           (Bionucleonics Laboratory, Purdue University, LaFayette,
           Indiana).   International Journal of Applied Radiation and
           Isotopes 8, 223-7, October 1960

ABSTRACT

This detector has a scintillator volume of one cubic foot and sample
chamber 4-1/3 inches in diameter and 8" long.   Four 5" photo-
multiplier tubes give a photocathode coverage of about 10% of the
detector's wall area.   Good light collection efficiency results in the
counter being relatively insensitive to source position in the sample
chamber.   The detector is housed in an iron shield providing 5 inches
of shielding.   Such detectors as the one described should find wide
application particularly in biological studies and clinical diagnosis
((Cs-137 was used as a calibration standard for the detector described
in this article)).

3.3.20   INTERACTION OF BETA DECAY AND SECOND FOR-
           BIDDEN SPECTRUM OF CESIUM-137.   Toshio Katoh,
           Shuichiro Yamasaki and Yasukazu Yoshizawa. (Depart-
           ment of Physics, Faculty of Science, Osaka University,
           Osaka, Japan.) Nuclear Physics 17, 548-62, July 1960

ABSTRACT

We discussed the allowed as well as non-unique first forbidden beta-
spectra and in particular the second forbidden spectra of Cs-137,

taking into account parity non-conservation. Our analysis can be summarized in the following way: From the consideration of Fierz terms in allowed as well as forbidden transitions, we can treat the two combinations STP and VA separately. Though a linear combination of the five interactions is possible no interference term between STP and VA exist. In the discussion of non-unique first forbidden transitions the combination VA is more favorable than STP. From the second forbidden spectrum of Cs-137 we see that $Re(C_x C_y + C'_x C'_y)/1C_y1^2 + 1C'_y1^2 \approx 1C_x1^2 + 1C'_x1^2$ where x and y mean s and f or v and a.

3.3.21 THE DESIGN AND APPLICATION OF A DEMOUNTABLE FOUR PI GEIGER MEULLER COUNTER. L. K. Burton, and N. G. Trott (Physics Department, Institute of Cancer Research, Royal Cancer Hospital, London) International Journal of Applied Radiation and Isotopes 8, 20-8, May 1960

ABSTRACT

An improved four Pi GM counter has been designed from which the cathode can be easily removed leaving the anode wire intact and still under tension. Counters of this type have been used successfully for several years in the measurement of radioactive nuclide standards and results of intercomparisons of standards with other laboratories are presented. The counters have also been used in conjunction with gamma ionization measurements in determining the specific gamma position (k factor) of Fe-59, Cs-137 and Ir-192. ((Applications of these counters in biological and medical work are described.))

3.3.22 ON THE DETERMINATION OF ABSOLUTE INTERNAL CONVERSION COEFFICIENTS BY THE COMPARISON OF CONVERSION LINES AND PHOTO LINES. AN APPLICATION TO THE 662-KEV TRANSITION IN THE DECAY OF CESIUM-137. Solve Hultberg and Rune Stockendal, Arkiv for Fysik, Vol. 14, No. 36, 565-77, 1959

ABSTRACT

The method for the determination of absolute values of internal conversion coefficients by the beta spectrometric comparison of conversion line and photo line intensities has been studied. The deduction of gamma ray intensities from measured photo lines is

treated and it is shown that experimentally determined photoelectric distributions can be used in the theoretical formulae to a good approximation. The instrument used was a flat double focusing beta ray spectrometer and general expressions are given for a source converter assembly of cylindrical symmetry about the spectrometer axis. An application was made to the 662-kev, M4 transition in Ba-137 and the conversion coefficient was found to be 0.093 ± 0.006. A 2.19 ± 0.02 mg/cm^2 uranium converter was used.

The activity ((used in the subject experiment)) consisted of 1 milli-curies of Cs-137 in one normal nitric acid and was obtained from the Radiochemical Center, Amersham. From this solution two radio-active sources were prepared; a strong one on a platinum backing by drop-wise evaporation and a weak one by vacuum evaporation. The sources were circular with a diameter of 6 millimeters. The weak source was intended for the internal conversion measurements and the strong one for recording photoelectrons from a uranium converter for the determination of the gamma ray intensity.

3.3.23   CONVERSION OF AMPLITUDE DISTRIBUTIONS INTO ENERGY SPECTRA. Yu A. Kazanskii, Pribori i Tekh, Eksptl, 4, 32-4, July-August 1959

ABSTRACT

The instrumental spectrum of pulse amplitudes and the efficiency of a single crystal scintillation gamma-spectrometer with a CsI(Tl) crystal were investigated. Using the data obtained, a number matrix was constructed by means of which using the method of successive sub-tractions, the amplitude pulse distributions were converted into energy spectra. For certain energy values of gamma radiation the efficiency, E_{pi}, of the spectrometer was determined by means of Cs-137, Cs-134, and Co-60 gamma radiation sources of known activity. The sources were placed at a certain distance from the crystal and a number of pulses in the photopeak were counted. Knowing the number of gamma quanta of given energy which were emitted by the source in unit time and by calculating the solid angle of the columnator it was possible to determine efficiency values for E = 0.661, 0.80, and 1.33 and 1.36 Mev which are shown by the dotted line in Figure 4. ((Figure 4 is not shown.))

3.3.24   BETA AND GAMMA RAYS SPECTROSCOPY OF CESIUM-137. Yasukazu Yoshizawa (Department of Physics, Faculty of Science, Osaka University, Osaka, Japan). Nuclear Physics 5, 122-140, Jan. 1958.

ABSTRACT

Beta rays and internal conversion electrons from Cs-137 have been studied using a 2-directional focusing beta ray spectrometer (mean radius = 40 centimeters). The K shell conversion coefficient alpha_K of 661 kev gamma transition has been determined to be 0.0976 ± 0.0051 and K/L/M to be $(5.66 \pm 0.04)/1/(0.260 \pm 0.003)$ which are in good agreement with Rose's calculated values for the M4 transition. The maximum energy of the lower component of the beta rays has been found to be 514 ± 2 kev. The curie plot, when corrected by the factor of the unique first forbidden transition, shows a straight line. The spectrum of the higher component was interpreted by the second forbidden correction factor with a linearity combination of scalar and tenser interaction. In an attempt to determine the sign of the ratio of scalar to tenser interaction constants, G_S/G_T, the spectrum could be only explained by the negative sign, assuming that the single particle model is a good approximation for the nuclear matrix element.

((End of Abstract))

Cs-137 as cesium-chloride was deposited on an aluminum foil of 1.8 mg/cm^2 thickness. The average thickness of the sample was about 0.2 mg/cm^2 and an acetic acid solution of insulin was used to make the source uniform. The beta ray and internal conversion spectra are shown in Fig. 1 where a strong conversion line is exhibited. ((Figure 1 is presented as Figure Cs7-1.))

3.2.25   REFER TO 3.2.17. RAPID ANALYSIS OF GAMMA EMITTERS USING A GAMMA-RAY SCINTILLATION SPECTROMETER. Chem.Soc. of Japan (Bull) 30, 583-5. Sept. 1957

3.3.26   PERFORMANCE OF A BETA SCINTILLATION SPECTROMETER SPECTRA AND CONVERSION COEFFICIENTS OF CESIUM-137 AND BISMUTH-207. R. A. Ricca (Instituut Voor Kernphysisch, Onberzuek, Amsterdam, Nederland, Physica, 23, 693-703. July 1957

ABSTRACT

The performance of a beta scintillation spectrometer (anthracene crystal) in nuclear spectroscopy has been investigated. A method of calibration of this spectrometer, is resolution and its response to

Cs-137 $\frac{7}{2}$ + Ba-137

514

$\frac{11}{2}$ -

1175

661

$\frac{3}{2}$ +
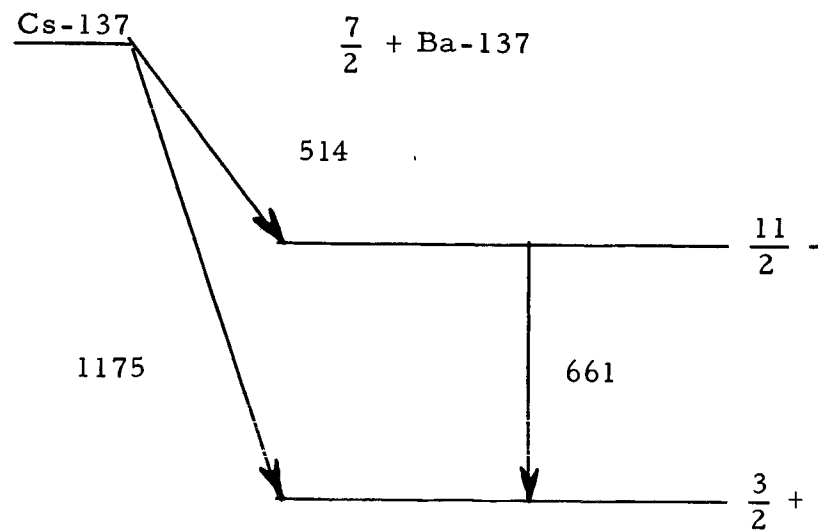
FIGURE Cs7-1. MOMENTUM SPECTRUM OF BETA RAYS OF Cs-137

different energies are reported. The nuclides Cs-137, Au-198, Bi-207, which have well known conversion lines, were used for the calibration. The function $(\Delta E)^2/E$ was plotted against the energy and found to be linear in the energy region considered. The spectra of P-32, Co-60, Au-198, and Cs-137 were analyzed. The total conversion coefficient of the 0.662 Mev gamma ray in the decay of Cs-137 was computed and found to be 0.114 ± 0.022. The K conversion coefficients of the two stronger gamma rays in the decay of Bi-207 were determined with the help of the measured gamma scintillation spectrum and found to be 0.019 (0.57)Mev transition) and 0.114 (1.06 Mev transition).

((End of Abstract))

We have tried to determine the total conversion coefficients of the 0.662 Mev gamma ray following the decay of Cs-137 and the decay coefficients of the two stronger gamma rays in the decay of Bi-207 with the help of the scintillation spectrometer. Cs-137 (Figure 7) shows the beta and conversion spectrum of Cs-137 ((Fig. 7 not shown)). The total conversion coefficient alpha$_{TOT}$ can be expressed as follows: Alpha$_{TOT}$ = x/(1-x); x = N_e/N_{BETA} = $S_E \mathcal{E}_{BETA} \mathcal{E}_E$. Where S_E and S_{BETA} are the areas under the conversion peak in the corresponding data spectrum. (Corrected for back scattering by extrapolation of the curie plot.) $\mathcal{E}_E = E_{BETA}$ we found Alpha$_{(TOT)}$ = 0.114 ± 0.222.

3.3.27   BETA INTERACTION IN THE DECAY OF CESIUM-137. Toshio Katoh, Masao Nozawa Yasukazu Yoshizawa (Department of Physics, Faculty of Science, Osaka University, Osaka) and Yujiro Koh (Faculty of Science Engineering, Osaka City University, Osaka). Journal of the Phys. Soc. of Japan 12, 738, June 1957

Recently it has been said that the ratio of $1G_s1/1G_t1$ in beta interaction is close to one. Its sign, however, has not been determined although some attempts have been done. The present paper concerns the trial for this problem investigating the spectrum of the higher components of the beta rays from Cs-137. A two-directional focusing beta ray spectrometer of mushroom type with the mean radius of 40 centimeters was used. The resolution of the spectrometer was 0.17 to 0.5%. It could be concluded from the measurements of P-32 and Y-90 spectra that the distortion due to the spectrometer was negligible. The thickness of the source was about 0.2 mg/cm^2.

3.2.28   THE HALF LIFE OF CESIUM-137.   F. Brown, G. R.
         Hall, and A. J. Walter (Atomic Research Establishment,
         Harwell, Didcot, Berks).   Journal of Inorganic and
         Nuclear Chemistry 1, 241-7, Oct. 1955

ABSTRACT

The beta decay half life of Cs-137 has been obtained from a specific
activity measurement.   The disintegration rate was measured in a 4
pi type proportional counter.   The number of atoms of Cs-137 was
measured by mass spectrometry using the isotopic dilution method.
The result is 30.0 + 0.3 - 0.4 years.   No allowance is made in this
error for uncertainties in the decay scheme used.

((End of Abstract))

((This paper describes how the half life has been obtained by means
of a specific activity determination.))   The Cs-137, a cesium-sulphate
solution was obtained from the Radiochemical Center, Amersham,
Bucks.   This cesium was of fission product origin and therefore
besides Cs-137 it contained Cs-133 (stable), Cs-136 3(10)^6 years, and
a small quantity of Cs-134 (2.3 years).   The radiochemical purity
was such that not less than 99.9% of the activity was due to Cs-134,
Cs-137, and Ba-137m (the daughter of Cs-137).   Cs-135 contributed
to the mass but hardly at all to the activity.   A master solution of
this material was prepared containing about 10 micrograms per milli-
liter of cesium and made slightly acid with sulfuric acid.   From this
solution a number of dilutions were prepared using water containing
various concentrations of natural cesium as carrier.

3.3.29   HALF-LIFE OF CESIUM-137.   D. M. Wiles and R. H.
         Tomlinson (Department of Chemistry, Hamilton College,
         McMaster University, Hamilton, Canada).   Physical
         Review 99, 188, July 1955.

ABSTRACT

The half-life of Cs-137 was found to be 26.6 ± 0.4 years by observing
the disintegration rate of a known number of atoms**.   The disinte-
gration rate was measured with a 4 pi proportional counter and the
number of atoms was determined from isotope dilution data obtained
with a mass spectrometer.

((End of Abstract))

A solution of carrier free Cs-137 was prepared from fission products by ion exchange techniques. Disintegration rate per unit volume of this solution was determined with a 4 pi proportional counter and the number of atoms of Cs-137 by means of isotope dilution with a mass spectrometer (The value of 26. 6 years is considerably lower than the currently expected value of 33 ± 2 years, calculated from comparison of the mass spectrometric ratios of Cs-133/Cs-137, in fission products differing up to 5 years in age.)

**((Presently accepted value = 30. 0 years.))

3 3. 30   INVESTIGATION OF THE NUCLEAR ISOMERISM OF
           Zn-69*, Se-79*, Se-81*, Rn-103*, and Ba-137*.
           G. M. Drabkin, B. I. Orlov, and L. E. Rusinov,
           Izvestia Akad Nauk, SSSR 12, 19, 324-37, May-June 1955

The radioactive isotopes Cs-137 decays by beta emission to Ba-137, T = 33 years   In 98% of a total number of disintegrations the beta decay of Cs-137 leads to the formation of the metastable Ba-137 nuclei which has a half life of 2. 6 minutes   The electron spectrum of Cs-137 and Ba-137 obtained by us is shown in Fig. 9.   The continuous beta spectrum and end point energy of 540 ± 10 kev belongs to Cs-137.   The K, L, and M lines are associated with the isomeric transitions of Ba-137* of energy 661 ± 2 kev.   The experimental value of K/L - 6. 0 ± 0. 1 is in agreement with the value of 6 for M4 transitions from the curve of Goldhaber and Suyar.   The decay scheme for Cs-137 is pictured in Fig. 9   The state of the stable Ba-137 nucleus is $d_{3}/2$; the metastable state of Ba-137* is $h_{11}/2$.   ((Figure 9, beta spectrum and decay scheme of Cs-137, is shown as Figure Cs7-2.))

3. 3. 31   NUCLEAR MATRIX ELEMENT FOR BETA DECAY AND
            THE RATIO OF COUPLING CONSTANTS. Jun-Ichi,
            Fujita (Department of Physics, Faculty of Science,
            University of Tokoyo). Progress of Theoretical Physics,
            13, 3, 260-4, March 1955

ABSTRACT

The nuclear matrix elements for the beta decay in the second and third forbidden transitions are derived on Bohr's collective model. The results are used for determining the ratio of the scaler and the tenser coupling constants in the analysis of the beta decay of Rb-87, Cs-137, Tc-99, and Fe-59 in terms of a linear combination of the scaler and the tenser Fermi interactions.

Cs-137

Ba-137*   ——— 661 kev

$K = 0.11 \pm 0.01$

M4 $K/L = 6.0 \pm 0.1$

$L/M = 4.1 \pm 0.4$

                                           ——— 0
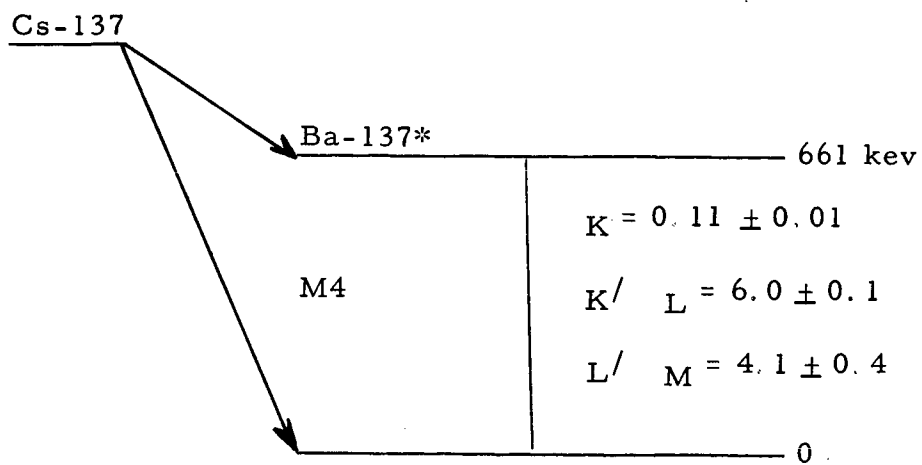
FIGURE Cs7-2.   BETA SPECTRUM AND DECAY
                SCHEME OF Cs-137

3.3.32   *ON THE CONVERSION SPECTRA OF THE ELEMENTS
          Ba-137 AND Ba-134. Julien Verhaeghe and Jean
          Demuynck. Compt. rend. 239, 1374-6 (1954) Nov. 22
          (In French)

3.3.33   *CONVERSION COEFFICIENT OF THE ISOMERIC
          GAMMA RAY IN THE DECAY OF BARIUM-137. A. H.
          Wapstra, Arkiv fur Fysik, 7, 3, 275-7, 1954

                        ABSTRACT

From beta spectrometer measurements on Cs-137, the K conversion
coefficient of the 662 kev transition in Ba-137m was found to be 0.093
$\pm$ 0.006 (M4 transition) and the K/L ratio 5.8 $\pm$ 0.3. The curie plot
is straight down to 75 kev if a special correction factor is used.

((End of Abstract))

Our active sample was prepared from the same carrier free Cs-137
used for determining the gamma energy and was spread with insulin
on an 0.15 mg/cm^2 aluminum backing.

3.3.34   INTERNAL CONSTANT EFFECT IN BARIUM-137.
          Larry Spruce and G. Goertzel (Physics Department,
          Washington Square College, New York University, New
          York, New York). Physical Review 93, 642, Feb. 1954

Continuous gamma rays accompanying internal conversion were
recently detected for the first time. The process bears the same
relationship to the Compton effect as internal pair production does to
pair production, and will be referred to as the internal Compton
effect. The ratio of the total number of gamma rays between 50 and
200 kev to the number of internally converted electrons was found to
be in crude agreement with the ratio predicted by the only theory
available, the semi-classical calculations of Wang Chang and Falkoff
but the angular distribution differed from the theoretical prediction.

3.3.35   INTERNAL CONVERSION COEFFICIENT OF BARIUM-
          137. Toshio Azuma (Physics Department, Naniwa
          University, Sakai, Osaka, Japan). Journal of the
          Physical Society of Japan, 9, 1-3, Jan-Feb 1954

ABSTRACT

((The)) internal conversion coefficient of Ba-137 has been investigated with a double coil magnetic lens beta ray spectrometer. The relative intensities of the internal conversion electron of the 663 kev gamma ray for K and L, L and M, energy levels have been estimated as 4.62 $\pm$ 0.18 and 15.0 $\pm$ 0.8, respectively. The value of K/L is in accord with the previous experimental values, and that of L/M is presented as a new value.

3.3.36   FISSION YIELDS OF STABLE AND LONG-LIVED ISOTOPES OF CESIUM, RUBIDIUM, AND STRONTIUM IN NUCLEAR SHELL STRUCTURE. D. R. Wilgs, B. W. Smith, R. Horsley, and H. G. Thode. Canadian Journal of Physics, 31, 419, 1953

ABSTRACT

The relative yields of the isotopes of cesium, rubidium, and strontium from thermal neutron fission of U-235 have been determined mass spectrometrically, The cesium isotope yields are combined with those obtained previously for the xenon isotopes to give high precision yields for the mass change from 131 to 137. In this work, neutron capture reactions have been considered and corrections made where these take place to an appreciable extent. The results give further evidence of abnormal yields in the 82 neutron shell region. The half life of Cs-137 was determined and found to be 33 $\pm$ 2 years. Cesium has been reported to have a half life from 33 to 37 years. The Cs-133 to 137 ratio will therefore increase with time. The data of Table 4 ((not shown)) may be used to calculate the half life of Cs-137. The results of these calculations are given in Table 5. It should be pointed out that some variation in the 133 mass yield may occur owing to neutron capture reaction, etc., which would introduce an error in the half life determination particularly for samples radiated at high flux values. ((A condensation of Table 5 is presented as follows.))

5 sample runs: results; 31, 31, 35, 35 years; average value = 33 $\pm$ 2 years.

3.3.37   BETA SPECTRA OF Fe-59, Rb-87, Tc-99, Cs-137 AND THE COUPLING CONSTANTS OF SCALAR AND TENSER INTERACTIONS IN BETA DECAY. Masato Morita, Jun-Ichi, Fujita, and Masarni Yamada (Department of Physics Faculty of Science, University of Tokoyo). Progress in Theoretical Physics, Vol. 10, No. 6, 630-40 December 1953

ABSTRACT

The beta spectra of Fe-59, Rb-87, Tc-99, and Cs-137 are investigated with the linear combination of scalar and tenser interactions in the Fermi-theory of beta decay, and it is inferred that the relative sign between two coupling constants of scaler and tenser interactions is minus.

3. 3. 38   THE MEASUREMENT AND INTERPRETATION OF THE
             K AUGER INTENSITIES OF Sr-113, Cs-137, and Au-198.
             C. D. Broyles, D. A. Thomas, and S. K. Haynes
             (Vanderbilt University, Nashville, Tennessee). Physical
             Review 89, 715-724 February 1953

ABSTRACT

Auger electron intensity measurements have been made on Cs-137, Au-198, and Sr-113, with a magnetic lens spectrometer which is briefly described. K auger yields for barium and mercury of 0. 130 $\pm$ 0. 007 and 0. 056 $\pm$ 0. 008, respectively, were recorded. The K auger electrons were resolved into three groups. K-LL, K-LX, and K-XY, according as 2, 1, or 0, no L electrons were involved. The ratios of the intensities of the latter two to the K-LL were found to be for In, 0. 417 $\pm$ 0. 016 and 0. 076 $\pm$ 0. 008, for ba, 0. 40 $\pm$ 0. 04 and 0. 08 $\pm$ 0. 02. The measured ratio of K-LX to K-LL for mercury was 0. 71 $\pm$ 0. 15. The relationship of these results to theory is discussed. A summary of measurements of K fluorescence yield and K auger line intensity ratios is given. The auger spectrum from Au-198 indicates that K capture to Pt-198 cannot occur in more than 0. 5% of the dis-integrations. A crude estimate of the L to K capture ratio for Sr-113 indicates that it is not abnormally high.

3. 3. 39   A PRECISION MEASUREMENT OF THE CESIUM-137
             GAMMA LINE. G. Lindstrom, K. Siegbahn, and
             A. H. Wapstra. (Nobel Institute for Physics, Stockholm,
             Sweden.) Proceedings of the Physical Society, (London)
             B66, 54-9, Jan. 1953

ABSTRACT

The recent establishment of a set of standard lines for precision work in beta ray spectroscopy is reviewed. In this work use was made of a semicircular spectrometer adjusted for high resolution. The proton

method for measuring the magnetic field and a large double focusing spectrometer. In this way absolute measurements of the lines were made as well as a number of different relative measurements. The general consistency is very satisfactory indicating a precision of the standard lines of one or two parts in 10^4. So far the following lines have been measured. The F, I, L, and K lines of Th(b, c''), the 411 kev line of Au-198, the annihilation radiation, the 2.75 Mev line of Na-21, the 662 kev line of Cs-137. In the present paper the measurements of the Cs-137 are described. The line has been studied as a conversional line and as a photo line emanating from a uranium converter. The combined results of the two spectrometers yield the following value of the energy of the Cs-137 line. E_{gamma} = 661.65 ± 0.15 kev. H_ρ value of the conversion line is 3381.28 ± 0.50 gauss centimeters.

((End of Abstract))

In order to get a uniform distribution of the cesium activity the insulin method of Langer (1949) was used. The activity was deposited on an aluminum foil with thickness 0.2 mg/cm^2 on an area of 4 x 18 mm^2. One may suspect a certain concentration of the activity at the edges of the rectangular area. A slit 2 mm x 13 mm placed on the aluminum foil masked off the dangerous regions. The same slit was used for the active Th source which is very uniform, being prepared in an activation vessel using a Rd Th sample.

3.3.40   PRECISION MEASUREMENTS OF NUCLEAR GAMMA RAY WAVELENGTHS OF Ir-192, Ta-182, RaTh, W-187, Cs-137, Au-198 AND ANNIHILATION RADIATION. David E. Muller, Harry C. Hoyt, David J. Klein, and Jesse W. M. DuMond (California Institute of Technology, Pasadena, California). Physical Review 88, 775-93, Nov. 1952

Measurements of the gamma rays from Cs-137, Au-198, and the annihilation radiation from Cu-64 were carried out after the calibration described above. The wavelength and energy of the single gamma ray following the decay of Cs-137 has been determined from the average of six measurements. The result in values are lambda = 18.737 ± 0.004 milliangstroms; E = 661.60 ± 0.14 kev.

3.3.41   NYO-869 STUDIES OF INTERNAL CONVERSION ELECTRONS FROM BARIUM-137. W. Kinney, B. Hildebrand. Progress Report AEC Contract by G. N. Glascoe, H. Landon, W. A. McKinley (Department of Physics, Rensselaer Polytechnic Institute, Troy, New York. Pg. 34, October 1952

(Under Table of Contents):

The L. Lamb, N. Reutherford, type field monitor now operates as an integral part of the beta ray spectrometer. A series of investigations on the internal conversion lines of Ba-137 was initiated with three principal purposes in mind.

1.   Determination of which of the L subshells is the principal contributor to the L conversion line and a similar study of the M line.

2.   A measurement of the ratio Alpha K/Alpha L. The ratio of the K to L internal conversion coefficients.

3.   A more precise determination of the Ba-137 gamma ray energy. The sources used in this study were two centimeters by one millimeter of area, density approximately 50 micrograms/cm^2 on aluminized backing of 100 micrograms/cm^2.

3.3.42   INTERNAL CONVERSION IN Pr-144, In-144, Ba-137, and Cd-110. W. C. Kelly, Physical Review 85, 101-3, Jan. 1952

ABSTRACT

Beta ray spectrometer measurements have been made of the internal conversion ratio $alpha_K/alpha_L$ for four nuclear transitions. Values obtained are 5.3 ± 0.1 for the 132 kev transition of Pr-144; 1.30 ± 0.05, 192 kev, In-144; 4.57 ± 0.05, 662 kev Ba-137; and 14 ± 2, 656 kev, Cd-110, tentative assignments of multipolarity are given.

((End of Abstract))

Three of the four radioactive materials were available at reasonably high specific activity. Cs-137 a parent of Ba-137 was obtained from Oak Ridge as CsCl at an activity of 1.05 millicuries/milliliter and with total solids not exceeding 2.4 mg/ml.

3.3.43   RADIOACTIVE DECAY OF Cs-137. M. A. Waggoner (Department of Physics, State University of Iowa, Iowa City, Iowa). Physical Review 82, 906-9, June 1951

ABSTRACT

The spins of the ground states of Cs-137 and Ba-137 are known to be
7/2 and 3/2, respectively. The shape of the 518-kev beta-ray
spectrum has been measured and found to correspond to the correction
factor $G' = (W_0 - W)^2 + A(W^2 - 1)$ in agreement with previous work.
This is the shape predicted by the Fermi theory of beta-ray decay and
the Gamow-Teller selection rules for a transition for which $I = \pm 2$
and there is a parity change. The internal conversion coefficient of
the 663-kev gamma-ray has been measured and found to be 0.097,
which is in agreement with the theoretical value for magnetic 2^4-pole
radiation.

3.3.44   REFER TO 3.7.36. THE L X-RAY SPECTRA FROM
         RADIOACTIVITY DECAY OF TRANSURANIUM ELEMENTS.
         Phys. Rev. 81, 208-13, 1951

3.3.45   MEASUREMENT OF CESIUM-137, AND COBALT-60
         GAMMA RADIATION WITH A PRESSURE IONIZATION
         CHAMBER.   G. R. Grove, Journal of Research,
         National Bureau of Standards, 48, 147-51, February 1951

ABSTRACT

The characteristics of the pressure ionization chamber at the
National Bureau of Standards have been studied for the gamma-
radiation from a Cs-137 source. (0.6614 Mev) and from a Co-60
source (1.1715 and 1.3316 Mev). The dosage rates produced in air
by these sources were measured with this chamber with an accuracy
of about 2%. Dosage rates obtained within extrapolation chamber and
a Victoreen thimble chamber agreed with the values measured by the
pressure chamber within the limits of the experimental errors.

3.3.46   INTERNAL CONVERSION OF GAMMA RAY FROM Cs-137.
         M. A. Waggoner (Department of Physics, State University
         of Iowa, Iowa City, Iowa).   Physical Review 80, 489, 1950

ABSTRACT

The present work yields (1) a value of 0.625 Mev for the energy of
the peak of the K internal conversion line, (2) a value of 0.518 Mev
for the end point of the low energy beta group, and (3) a spectrum
shape for the 0.518 Mev beta group which gives a straight Fermi plot

when corrected by the correction factor G' and thus indicates that this transition involves a spin change of two with a change of parity. All of these results are in agreement with those of Osaba**.

**Phys. Rev. 76, 345, 1949

3.3.47   A PRECISE DETERMINATION OF THE ENERGY OF THE CESIUM-137 GAMMA RADIATION. Lawrence M. Langer and R. Douglas Moffat (Indiana University, Bloomington, Indiana). Physical Review 78, 74-75, 1950

ABSTRACT

In an attempt to establish Cs-137 as a calibration standard, the energy of the internal conversion electrons has been carefully determined by direct comparison with that of the 0.4112 Mev gamma ray of Au-198. A composite source of Au-198 and Cs-137 was prepared on a 0.00025 inch aluminum backing. The source was 0.25 centimeters wide and 2.5 centimeters high, and was spread with the aid of insulin. The source thickness was estimated to be 0.03 mg/cm^2 of Au-198 and 0.1 mg/cm^2 of Cs-137. ((The gamma energy in Mev for Cs-137 was found to be 0.6614 ± 0.0007))

3.3.48   THE BETA SPECTRA OF Cs-137, Y-91, Pm-147, Ru-106, Sm-151, P-32, and Tm-170. Harold M. Agnew. Physical Review 77, 655-60, March 1950

PARTIAL ABSTRACT

The beta spectra of Cs-137, Y-91, Pm-147, Ru-106, Sm-151, P-32, and Tm-170 have been investigated using a large double magnetic lens spectrometer. The investigation of these materials was carried out with sources whose thicknesses were less than 0.1 mg/cm^2. The sources were mounted on thin foils in such a manner that they did not accumulate charge. Cs-137 and Y-91 were found to have distinctly non-linear Fermi plots. Ru-106, Pm-147 and Sm-151 have linear Fermi plots, and the Fermi plot of Tm-170 is slightly curved. Auger electron have been found associated with the Ba-137 decay product of Cs-137. The end points of the continuous beta ray spectra of those materials have been determined as follows: Low energy group of Cs-137, 0.323 ± 0.004 Mev, ------, Pm-147, 0.229 ± 0.001 Mev.

((End of Abstract))

((Those parts of the abstract not dealing with Cs-137 or Pm-147 have been omitted.))

The sources were mounted on either zapon or LC600 films weighing less than 0.01 mg/cm^2.

3.3.49   THE RESPONSE OF THE ANTHRACENE SCINTILLATION
         COUNTER TO MONO-ENERGETIC ELECTRONS.   John I.
         Hopkins (Oak Ridge National Laboratory, Oak Ridge,
         Tennessee).   Physical Review 77, 406-7, Feb. 1950.

Approximately 50 microcuries of Cs-137 evaporated on a thin formvar film served as a source of electrons.

3.3.50   ATOMIC BEAM MAGNETIC RESONANCE EXPERIMENTS
         WITH RADIOACTIVE ELEMENTS Na-22, K-40, Cs-135
         and Cs-137. Luther Davis, Jr. , Darragh E. Nagle, and
         Jerrold R. Zacharias (Department of Physics and Research
         Laboratory of Electronics, Massachusetts Institute of
         Technology, Cambridge, Massachusetts).   Physical
         Review 76, 1068-75, Oct. 1949

ABSTRACT

Modifications of the atomic beam magnetic resonance method for the determination of nuclear spins and moments by observation of the hyperfine structure of atomic ground states are described, which make it possible to work with very small quantities in samples with low concentration.   These modifications include the analysis of the beam by means of a mass spectrometer while performing the resonance experiment.   A new source of beams of atomic alkali metals is described.

3.3.51   BETA SPECTRA OF FORBIDDEN TRANSITIONS.
         Lawrence M. Langer and H. Clay Price, Jr. (Department
         of Physics, Indiana University, Bloomington, Indiana).
         Physical Review 76, 641-6, Sept. 1949

ABSTRACT

The beta spectra of the forbidden transitions Y-91, Sr-89, Y-90, Cs-137, RaE, Au-198, Re-186, and P-32 have been measured with thin sources and high resolution.   Forbidden type spectra are found

for the first five, Au-198, Re-186, and P-32 yield spectra with the allowed shape. Evidence is advanced for the reliability of the nuclear shell structure model and for the validity of GT selection rules. End points found are Y-91, 1.537 ± 0.007 Mev; Sr-89, 1.463 ± 0.005 Mev; Y-90, 2.180 ± 0.007 Mev; Cs-137, 0.51 ± 0.01 Mev; Au-198, 0.965 ± 0.005 Mev; Re-186, 1.063 ± 0.006; and P-32, 1.689 ± 0.01 Mev.

((End of Abstract))

The data on the Cs-137 distribution were obtained with several sources, the thinnest of which had an average thickness of 0.03 mg/cm^2 and the thickest was 0.2 mg/cm^2.

3.3.52   THE FORBIDDEN TRANSITION OF YTTRIUM-91 AND CESIUM-137. J. Osoba (Department of Physics, Washington University, St. Louis, Missouri). Physical Review, Vol. 76, 345-9, August 1949

ABSTRACT

Yttrium-91 decays by the emission of a single beta particle with a maximum energy of 1.54 Mev, while Cs-137 decays in two ways. (1) Beta decay (maximum energy = 0.518 Mev), to Ba-137 followed by a gamma transition to the ground state and (2) Beta decay (maximum energy = 1.2 Mev) directly to the ground state. Probably not more than 5% of the Cs-137 nuclei decay directly to the ground state. Conventional (allowed transition) Curie plots of Y-91 in the low energy group of beta particles of Cs-137 display curvature which is concave toward the energy axis at high energies in concave upward at low energies. It is assumed that the Gamow-Teller selection rules govern the beta process, the Fermi-function, $F(Z, W)$, for allowed spectra must be multiplied by a factor $G = (W^2 - 1) + (W_O - W)^2$ in a beta transition for which there is a change of parity, and for which the spin change is 2 units. If these conventional Curie plots of Y-91 and Cs-137 are modified by the factor G, the resulting plots are approximately straight lines. This indicates that the beta decay of Y-91 and the low energy beta decay of Cs-137 involve a spin change of 2 units and a parity change. These results contribute evidence for the validity of the Fermi theory of beta decay in the Gamow-Teller selection rules. The K internal conversion coefficient for the 0.663 Mev gamma from the decay of Cs-137 was found to be 0.081 while the ratio of the K conversion electrons to the L conversion electrons was 5.0. The gamma radiation seems to be either magnetic 2+ pole or electric 2+ pole.

((End of Abstract))

Radioactive sources were prepared by first defining the source area with insulin on a thin Zapon film about 0.03 mg/cm^2 thick. The active material in solution was then applied to this area and fast dried under an infrared lamp. ((The author feels it would be useless to give a figure for the source thickness since the active deposit seemed to be in small crystals.)) Previous work done at this laboratory indicated that Cs-137 decays by simple beta emission to a metastable state, Ba-137 which then decays (half life = 158 seconds) to the ground state of Ba-137 by the emission of a 0.663 Mev gamma ray. The present investigation confirms the result obtained by Mitchell and Peacock** that the decay of cesium occurs in 2 ways ((as described in abstract)). As will be shown probably not more than 5% of the Cs-137 nuclei decay directly to the ground state.

**Physical Review 75, 1272, 1949.

3.3.53 DISINTEGRATION OF CESIUM-137. Charles L. Peacock and Alan C. G. Mitchell (Indiana University, Bloomington, Indiana). Physical Review 75, 1272-4, April 1949

Decay by emission of a single group of beta rays with an end point of 0.550 Mev to a metastable state of Ba-137 (156 seconds) has been reported for Cs-137 (33 years) from this state an internally converted gamma ray of energy 0.663 Mev is emitted. A simple decay scheme was suggested from these results. Mitchell and Peacock measured the ratio N_K/N_L for the internally converted electrons as well as the internal conversion coefficient αK_L. The measurement of these quantities as well as the known half-life for the metastable state indicate that the transition Ba-137 (metastable) $\longrightarrow$ Ba-137 is electric 2+ pole. They also pointed out certain difficulties with the proposed decay scheme. In the present experiment the beta ray spectrum of Cs-137 has been measured using 180° type magnetic spectrometer of about 1% resolving power. The spectrum consists of 2 groups. The main group having an energy of 0.521 Mev and relative abundance 95% and a much weaker group having an energy of approximately 1.2 Mev and a relative abundance 5%.

The source used in this portion of the work had a surface density of not greater than 0.1 mg/cm^2 mounted on Zapon of 0.01 mg/cm^2. A thicker source was used to investigate the higher energy beta rays since this group is only 5% abundant. The energy of the gamma ray causing the internal conversion electron has been measured and found to be 0.669 $\pm$ 0.005 Mev. In addition, a line of very low intensity appears at 25 kev

and can be ascribed to auger electrons arising as a result of an internally converted gamma ray. The gamma ray and the two beta ray groups appear to form a consistent energy level scheme.

3.3.54   ON THE Cs-137 DISINTEGRATION SCHEME. Alan C. G. Mitchell and Charles L. Peacock (Indiana University, Bloomington, Indiana). Physical Review 75, 197, Jan. 1949

The beta and gamma ray spectrum of Cs-137, 33 years, has been measured by Townsend, Owen, Cleland and Hughes**, who find that the beta ray spectrum is simple with an end point at 0.550 Mev. In addition, there is only one gamma ray of energy of 0.663 Mev which is internally converted. Later the same authors showed that there were no coincidences between the beta and gamma rays and proved that the beta disintegration leads to a metastable state of Ba-137 which has a half life of 158 ± 5 seconds. The gamma ray is emitted from this metastable state.

The K and L internal conversion lines of the 0.663 Mev gamma ray have been resolved, and the ratio N_K/N_L has been determined by several investigators. The best value for this ratio is 4.8 ± 0.3. In addition the internal conversion coefficient alpha$_K$ has been measured and is 11.8% ((The balance of the article is concerned with spin in magnetic moments and is not reproduced here.))

**Phys Rev 74, 499, 1948.

3.3.55   THE DISINTEGRATION OF Cs-137. J. Townsend, Marshall Cleland, and A. L. Hughes (Department of Physics, Washington University, St. Louis, Missouri). Physical Review 74, 499, Aug. 1948

In a previous letter** it was reported that Cs-137 (33 years), has a simple beta spectrum and an end point energy of 0.550 Mev and a gamma ray of 0.663 Mev energy partially internally converted (12%). Subsequent coincidence counting experiments revealed no beta-gamma coincidences. However, coincidences were found between conversional electrons and the associated X-rays. A critical absorption experiment to determine the X-ray energy was performed by placing aqueous solutions containing Sn, Sb, Te, and I, between the source and one of the counters. The X-rays were found to be characteristic of barium indicating that the gamma rays are emitted from the excited

barium nuclei which follow the beta decay of cesium.   The long half life of the Cs-137 and excited Ba-137 nuclei indicated that large spin charges are involved in both beta and gamma transitions.   The spin of the ground state of Ba-137 is known to be 3/2.

3.3.56   BETA AND GAMMA SPECTRA OF Cs-137.   J. Townsend, G. E. Owen, Marshall Cleland, and A. L. Hughes (Washington University, St. Louis, Missouri).   Physical Review 74, 99-100, July 1948

An investigation in this laboratory on the absorption of gamma rays called for the use of radioactive isotopes emitting monoenergetic gamma rays.   Among those used was Cs-137, a fission product of high specific activity, produced by the Clinton Laboratories at Oak Ridge, Tennessee.   ((The subject investigation showed that.))   The radiation from Cs-137 consists of a simple beta ray spectrum with an end point at 0.550 Mev energy and a single gamma ray of 0.663 Mev energy, 12% of the gamma ray being internally converted.   The mono-energetic nature of the gamma ray combined with the long half life of Cs-137, 33 years, suggests its use as a gamma ray standard.   Coincident studies are being made to secure information as to the decay scheme of this isotope.

I.   HALF LIFE

2, 620 ± 0.005 ----- Ref. 3.4.5 HW-SA-3698,
                May 1964

II.   DECAY SCHEME AND ENERGY LEVELS

Pm-147 ──▶ Sm-147

Beta, 0.226 Mev (100%) ---- Ref. 3.4.27 Phys.
                                Rev. 105, 241-6,
                                Jan. 1957

No gamma ---- Ref. 3.4.11 HW-771375, April
                1963

Pm-147 _____

β^- ?
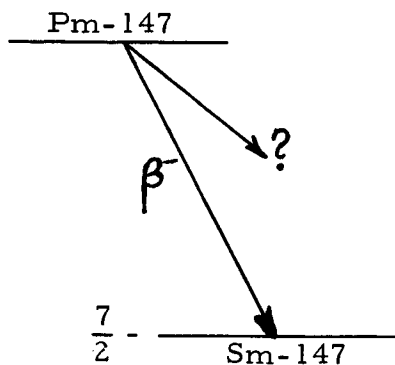
Ref. 3.9.5 Rev. Mod.
Phys. Vol. 30, #2;
Pt. 2, April 1958

$\frac{7}{2}$ - _____
        Sm-147

3. 4. 1   +ON THE MEAN BETA DISINTEGRATION ENERGIES OF
            Pr-143, S-35, AND Pm-147.   Vaeinoe Hovi, Lasse
            Niemelae, and Jorma Varonen (Univ. of Turku, Finland).
            Ann. Acad. Sci. Fennicae, Ser. A VI, 150: 1-12 (1964)

ABSTRACT

By using an isothermal microcalorimetric method and radioactive beta
sources, the mean beta disintegration energies of Pr-143 and S-35
were measured at liquid nitrogen temperature.   The activity of these
sources was known with a great accuracy.   The measured values of
the mean beta disintegration energy, 310 and 48. 8 kev for Pr-143 and
S-35, respectively, are in very good agreement with those obtained
from Fermi's theory and from experimental beta spectra.   The mean
beta disintegration energies of S-35 and Pm-147 were also determined
by means of a scintillation spectrometer in which an anthracene split-
crystal was used.   (Auth)

3. 4. 2   THE EXTERNAL BREMSSTRAHLUNG PRODUCED IN
            THIN FOILS BY Pm-147.   Vincent C. Truscello -
            Joseph Silverman.   Paper presented at the Symposium
            on Low Energy X and Gamma Sources and Applications,
            October 20, 21, 1964, Chicago, Illinois.   Sponsored by
            the Atomic Energy Commission.

INTRODUCTION

A NaI(Tl) scintillation spectrometer was used in conjunction with a
512-channel pulse height analyzer to study the spectral distribution of
the external bremsstrahlung produced by Pm-147 betas (E_{max} = 223
kev) in thin foil targets.

A thin source of Pm-147 (mass thickness of 0. 3 mg/cm^2) was prepared
by depositing 23 microcuries of this radionuclide on a sheet of alumi-
nized mylar (0. 6 mg/cm^2).   The bremsstrahlung was produced by thin
foil targets ranging in thickness from 1 to 70 mg/cm^2 and in atomic
numbers from 13 to 73.   The bremsstrahlung was found to have a
linear dependence on the atomic number of the target material as
predicted by theory.   It was further determined that the experimental
data could be represented by the empirical relations:

        Photon yield   = 3. 7 x 10^{-5} Z photons/beta particle
        Photon intensity = 1. 8 x 10^{-6} Z Mev/beta particle

3.4.3   +THERMAL POWER OF PROMETHIUM-147.   J. C. Posey,
         R. S. Pressly, and J. H. Gillette (Oak Ridge National
         Laboratories, Tennessee).   Trans. Am. Nucl. Soc. , 7:
         207-8, June 1964

3.4.4   +THE MEASUREMENT OF AQUEOUS SOLUTIONS OF
         METALLIC RADIOISOTOPES BY LIQUID SCINTILLATION
         METHODS.   A. Dyer, J. M. Fawcett, and D. U. Potts
         (Royal Coll. of Advanced Tech. , Salford, Lancaster,
         England).   Intern. J. Appl. Radiation Isotopes, 15: 377-80
         June 1964

Determination of Ag-110m, Na-22, Pm-147, and Tl-204 in aqueous
solutions by scintillation methods is described.

3.4.5   HW-SA-3698 CALORIMETRIC DETERMINATION OF THE
         MEAN BETA ENERGY AND HALF LIFE OF PROMETHIUM-
         147.   E. J. Wheelwright, D. M. Fleming, F. P. Roberts
         (Hanford Laboratories, General Electric Company,
         Richland, Washington).   20 May 1964 ((to be published in
         forthcoming issue of Journal of Physical Chemistry)).

ABSTRACT

The mean beta energy of the Pm-147 decay has been calorimetrically
measured at periodic intervals extending over a one-year period.   Two,
independently prepared, thousand curie sources of highly purified
Pm_2O_3 were examined.   The results obtained by the authors are self-
consistent and are in excellent agreement with measurements made on
the same sources by an independent scientist using a second calorim-
eter.   Values of 0.3330 ± 0.0005 watt/gram Pm-147 and 2.620 ±
0.005 years for the beta-decay energy and the half-life, respectively,
are believed to be the most reliable values yet published.

((End of Abstract))

The Pm-147 used for the experiment was recovered as a crude rare
earth fission product mixture from Hanford waste by precipitation
processes.   The crude mixture containing 20,700 curies of Pm-147
was then processed through a multi-column ion exchange unit in the
Hanford Laboratories "hot cells" to separate the Pm-147 from its
adjacent rare earth neighbors and all other contaminants.

((The purity of source one and two were measured to be 99.9 ± 0.1% and 99.0 ± 0.2%, respectively.))

((The following table presents the results of the experiment on the two promethium samples.))

	Source 1	Source 2
Date Purified	0030 hours 14 January 1963	0030 hours 14 January 1963
Grams of Pm-147 in source	1.4089 ± 0.0014	1.2063 ± 0.0024
Curies of Pm-147 in source	1310 ± 1	1120 ± 3
Pm-147 mean beta energy (watts/gram)	0.3335 ± 0.0006	0.3325 ± 0.0007
Pm-147 half life (years)	2.620 ± 0.005	2.620 ± 0.005

3.4.6   ISOTOPIC POWER DATA SHEETS.   S. J. Rimshaw (Oak Ridge National Laboratory, Oak Ridge, Tennessee).   For presentation at the Industry Information Meeting on Isotopic Power Development and Applications, Washington, D.C., May 18-19, 1964

Source Material	Pm_2O_3
Half-Life	Pm-147 - 2.67 years
Decay and Radiation Properties	Pm-147 Sm-147 (stable) Beta Gamma 0.225 Mev (100%) none
Isotopic Composition	100% Pm-147
Radiochemical Purity	About 1% Pm-148 ($T_{1/2}$ = 42 days) will be present 4 months after discharge from a reactor. With a cooling time of two years, the Pm-146 ($T_{1/2}$ = 1.94 years) content will be 5×10^{-5}% of the Pm-147 activity, and the Pm-148 activity will be less than the Pm-146 activity.
Chemical Purity	95% Pm-147 principal impurity is Nd at last separation time. Purity can approach 99%, but will decrease as stable Sm-147 daughter grows in.

Specific Power	0.41 watts/kilocurie of Pm-147 or 0.324 watt/gram of pure Pm_2O_3.
Thermal Energy	2440 curies per thermal watt.
Density	Theoretical density is 7.3. Practical production density is 90% of the theoretical density, or 6.6 g/cm^{-3}.
Power Density	2.03 watts/cm^{-3} based on 95% Pm_2O_3 and a density of 6.6 g/cm^{-3}.
Thermal Conductivity	Values for typical rare earth oxides are about 0.006 cal/sec· cm· °C at 150°C.
Specific Heat	0.0944 cal/g from 0° to 1000°C for Sm_2O_3.
Coefficient of Expansion	10.8 x 10^{-6}/°C from 30° to 740°C for Sm_2O_3.
Melting Point	2350°C for Sm_2O_3.
Mechanical Strength	For Sm_2O_3: Modulus of Rupture = 2000 lb/in^2 at room temperature. Modulus of elasticity (sonic) = 26.5 x 10^{-6} lb/in^2 at room temperature.
Thermal and Radiation Stability	Fabricated sources have exhibited good stability for several years.
Radiation Attenuation	Shielding required is small for Pm-147. Shielding requirements are established by the Pm-146 and Pm-148 content. Refer to "Shielding Requirements for Promethium Sources," HW-77375, and "Radiation Characteristics and Shielding Requirements of Isotopic Power Sources for Space Missions,"

	ORNL-TM-591 (Rev.). Also, refer to "Handbook of Shielding Requirements and Radiation Characteristics of Isotopic Power Sources for Terrestrial, Marine and Space Applications," ORNL-3576.
Gas Evolution Due to Radio-active Decay Processes	None
Leach Rate	No data available. Most fired rare earth oxides hydrate and disperse in boiling water.
Vapor Pressure	No data available.
Resistance to Thermal Shock	No data available.
Burnup Characteristics	Dispersibility poor.
Capsule Compatibility	Excellent with most metals.

3. 4. 7   CONSTRUCTION OF A PROMETHIUM-147 ATOMIC BATTERY. H. Flicker, J. J. Loferski and T. S. Elleman, IEEE Transactions on Electron Devices, January 1964

ABSTRACT

The feasibility of constructing an atomic battery by combining the beta emitting radio isotope Pm-147 and a semiconductor containing a PN junction has been studied, both theoretically and experimentally. Properties of cells made by diffusing a P type impurity into an N type GaAs P impurity into N type silicon (n/p) are compared. The problems associated with the presence of an alpha emitting impurity Am-241 in the Pm-147 and with the fabrication of a suitable Pm-147 source are considered. Experiments with prototype batteries composed of Pm-147 and N/P silicon cells have lead to the conclusion that such batteries would have a half life of 1.6 years, somewhat shorter than that of Pm-147 (2.6 years). Such a battery could generate a few milliwatts of power from a volume of about 2 cubic inches including shielding. ((Table 1, properties of Pm-147 is presented as follows:))

E_{max} = 230 x 10³ ev, max energy of beta particles

$E_{\beta\,av}$ = 73 x 10³ ev, average energy of beta particles

t_H = 2.6 years, half life

G = 980 curies/gm, specific activity

I_{max} = 1.1 x 10⁻⁸ amps/cm², self absorption limited electron current which would be emitted from a surface of a semi-infinite layer.

$ZE_{\beta\,av}I_{max}$ = 1.7 x 10⁻³ watts/cm², maximum power emitted from both faces of a thick planar source.

α_0 = 1300 cm⁻¹, self linear absorption coefficient of Pm-147 beta rays.

α_0/ρ = 150 cm²/gm, mass absorption coefficient of Pm-147 beta rays.

3.4.8 *CEA-2355. ETUDE DU SCHEMA DE DESINTEGRATION ET DES MOMENTS ANGULAIRES DES NIVEAU EXCITED DU Pm-147 PAR DES MESURES DE SPECTROGRAPHIE ET DE CORRELATIONS ANGULAIRES (these). (Study of the Disintegration Process and of the Angular Moments of the Excited Levels of Pm-147 Using Spectrographic and Angular Correlation Measurements (thesis). Claude Philis France. (Commissariat a l'Energie Atomique. Centre d'Etudes Nucleaires, Saclay). 1963, 87 p. (In French.)

The energies and relative intensities of fifteen gamma lines were determined by a direct spectrographic study. A previously unreported level at 77 ± 2 kev was identified. A coincidence study confirmed the positions of the excited levels of Pm-147. The 77-kev line was placed between the 409 and 490-kev levels. Angular correlation measurements permitted the assignment of angular moments of 5/2 or 7/2 to the 685-kev level. The associated mixing coefficients were also obtained.

3.4.9   EXCITED STATES OF Pm-147.   E. Spring (Department
         of Physics, University of Helsinki, Finland).   Physics
         Letters 7, 3, 218-9, November 1963

The present work relates to continued study of Pm-147 and has as ((its))
aim a systematic study of singles and coincidence spectrum, and fixing
the spins for a number of the excited states by means of angular
correlation measurements.   In this investigation, use was made of a
source of Nd-147 in solution obtained from Harwell.   The source had
the form of a cylinder 2 mm in diameter and 5 mm in length.   All
spectra were measured 4-6 weeks after radiation to avoid disturbances
arising from activities of shorter life.   Several single spectra were
measured and analyzed.   The pulse height spectra of gamma rays in
coincidence with the following gate pulses were recorded: 85-110 kev,
110-135 kev, 135-160 kev, 170-190 kev, 190-230 kev, 240-280 kev,
380-440 kev, 440-480 kev, 530-570 kev, 580-620 kev, and 670-710 kev.
The decay scheme ((for Nd-147)) proposed in Figure 1 (not shown) is
based on these measurements.   The relative intensities are expressed
as percentages of the intensity of the 531 kev gamma transmission.
The errors are $\pm$ 10% of the absolute intensity for the strong transitions
but increase to $\pm$ 50% for the weak ones.

3.4.10   RAI-202.   THE DEVELOPMENT OF LARGE BETA
          RADIATION SOURCES AND THEIR APPLICATIONS.
          Jacques J. Weinstock, Yael Miron, and P. Murali
          Krishma (Radiation Applications, Inc., Long Island City,
          N. Y.).   July 1963.   140 p.

An extensive research and development program produced vitreous
enamel formulations suitable for the fabrication of a large planar beta
radiation sources using Pm-147, Ce-144 or Sr-90 as the active
component.   The physical and chemical properties of these enamels
were characterized, and actual source dosimetry patterns were
established for Pm-147 and Ce-144 sources.   These enamels allow
the fabrication of beta sources containing up to 5 curies per square
centimeter of Pm-147 in a 4-mil thick coating, up to 5 C/cm^2 of Ce-
144 in an 8-mil coating, and up to 1 C/cm^2 of Sr-90 in an 8-mil
coating.   Such sources will deliver surface and near surface dose
rates in the range of 1 to 10 megarads per hour.   Actual dosimetry
patterns are presented for enameled Ce-144 and Pm-147 sources
containing approximately 0.1 millicurie per square centimeter.   These
dosimetry measurements are compared with theoretical calculations
and show generally good agreement.

3.4.11   HW-77375.   SHIELDING REQUIREMENTS FOR
          PROMETHIUM SOURCES.   H. H. Van Tuyl, F. P.
          Roberts, E. J. Wheelwright (Hanford Atomic Products
          Operation, Richland, Washington.   April 1963.

A theoretical analysis of the shielding required for large amounts of
promethium was made, including an analysis of the radiation
contributions from Pm-146 and Pm-148 at different times after
reactor discharge.   The results are compared with experimental
determinations on samples of promethium at different ages, and
promethium is compared with other radionuclides which may be used
in power sources.   As a first approximation, shielding requirements
for promethium aged less than 2 years from reactor discharge are
comparable to those for Sr-90 or Cs-137.   For promethium aged over
2 years, shielding requirements are comparable to those for Pu-238.
Shielding an aged (over 2 years) promethium oxide source to 10 mr/hr
at 1 meter would require about 1/4 inch of uranium for a 100 watt
source, and 2/3 inch for a 1000 watt source.   For optimum geome-
tries, these shield weights correspond to 3 and 4 times the source
weight, respectively.   Shielding to a dose rate of 1 r/hr at 1 meter
would require shielding of weight less than one tenth of the source
weight.   The former case would permit close approach of personnel,
while the latter would afford ample protection for most auxiliary
equipment.

3.4.12   HW-77296.   THE HALF LIFE OF PROMETHIUM-147.
          F. T. Roberts, E. J. Wheelwright, and W. Y. Matsumoto
          (Hanford Atomic Products Operation, Richland, Washington,
          General Electric Corporation) April 1963

ABSTRACT

((This report describes a Pm-147 half life determination based on
absolute beta counting of a solution prepared from a weighted amount
of very highly purified promethium oxide.))   The specific activity of
Pm-147 has been determined to be $2.026 \pm 0.048 \times 10^{15}$ disintegration/
minutes/gram which corresponds to a half life of 2.67 ± 0.06 years.
This value was obtained by 4 pi beta counting known amounts of
promethium.   The chemical purity of the promethium was verified by
emission in absorption spectroscopy and by chelometric titration.
The promethium used to prepare a standard solution was purified from
Hanford fission product waste.   The recovery process was a chroma-
tographic displacement technique from which more than 10 grams of

highly purified promethium was obtained.   The promethium used in
making the standard solution was taken from the center of the elution
band to insure maximum chemical and radiochemical purity.
Promethium was precipitated as the oxolate after filtering and washing
with dilute oxolate acid the precipitate was ignited at 750°C for 6 hours
to convert to the oxide.   A sample of the prepared oxide was accurately
weighed, dissolved in 1.0 molar $HClO_4$ abd diluted to a known volume
with 1.0 molar $HClO_4$.   This solution was used in all experiments.
The purity of the promethium was checked by emission spectroscopy
and found to contain only trace amounts of metallic impurities.   Radio-
chemical analysis show no detectable impurities other than Pm-146 and
Pm-148.   Both of these activities were less than 10^{-4}% of that of Pm-
147.

3.4.13   +MEASUREMENTS OF THE MEAN BETA DISINTEGRATION
            ENERGIES OF P-32 AND Pm-147 AT LOW TEMPERA-
            TURES.   Vaeinoe Hovi and Lasse Niemelae (Univ. of
            Turku, Finland).   Ann. Acad. Sci, Fennicae. Ser. A, VI,
            No. 103, 1-10 (1962)   (In English)

By using an isothermal microcalorimetric method the mean beta
disintegration energies of P-32 and Pm-147 were determined at liquid
nitrogen temperatures.   Taking into account the bremsstrahlung
correction, the value of 691 ± 20 kev was obtained for the mean beta
disintegration energy of P-32, in agreement with experimental data
and Fermi's theory.   In the case of Pm-147 the measured mean beta
disintegration energy was 70.4 ± 4 kev, about 10% higher than that
obtained from the beta spectrum and the Fermi theory.

3.4.14   ACCURATE MEASUREMENT OF THE HALF LIFE OF
            THE 91 KEV STATE OF PROMETHIUM-147.   Beekhuis
            H. Physica 28, 1199-1200, 1962

ABSTRACT

A half life of 2.59 ± 0.02 nanoseconds (estimated probable error) was
found for the 91 kev level in Pm-147 excited in the beta decay of Nd-
147 from delayed coincidence measurements between beta rays and L
conversion electrons.

3.4.15   LOW ENERGY PHOTON EMISSION FROM RADIOISOTOPES.
            Farno L. Green, Transactions of the American Nuclear
            Society 5, 1, 207, June 1962

ABSTRACT

This paper is primarily concerned with the emission rates of low energy photons allowed by nature. The low energy range considered is approximately 20 to 300 kev. Table 1 ((not shown)) presents the theoretical maximum number of photons in a metallic source of two millimeters diameter and two millimeters length in which every atom is considered to be radioactive. ((In addition to several other isotopes, the following information is given for promethium: half life, 2.6 years; disintegration rate (curies per pellet), 46; approximate photons per disintegration, 0.03; approximate photons per second, 5.2×10^{10}.

3.4.16   HALF LIVES OF RADIO NUCLIDES--II.   E. I. Wyatt, S. A. Reynolds, T. H. Handley, W. S. Lyon and H. A. Parker (Analytical Chemistry Division Oak Ridge National Laboratory, Oak Ridge, Tennessee). Nuclear Science and Engineering 11, 74-75, 1961

ABSTRACT

Half lives of 21 radionuclides are reported. In general the activity of a purified sample was followed for two or more half lives. The data were analyzed by least squares using desk calculators or computers. Two half life values reported previously have been redetermined with improvement.

((End of Abstract))

((Determination for promethium-147 is as follows: half life, 2.50 ± 0.03 years; time observed in half lives, 2.0; instrument used for half life determination, a 2 pi internal source gas flow proportional counter.))

3.4.17   DIRECTIONAL CORRELATION OF GAMMA TRANSITIONS IN PROMETHIUM-147.   Babulai Sarat, Jambuyairan, and M. R. Gonte (Atomic Energy Establishment Trombay, Bombay, India). Physical Review 124, 178-82, October 1961

ABSTRACT

The angular correlations of five different gamma ray cascades involving the states of Pm-147 excited in the decay of Nd-147 have

been studied. The observed correlation functions for the various cascades are presented. The analysis of the above correlation functions with the ground state spin of promethium-147 as 7/2 and the consideration of the log ft value for the beta transitions from Nd-147 state of spin 5/2 give the spin values for the 91, 413, 491, 533, and 690 kev excited states as 5/2, 7/2, 7/3, 5/2 and 5/2, respectively. The data of Bishop, et al, and Ambler, et al, on nuclear alignment experiments have been re-analyzed. Results are consistent with the above spin assignment for 5/2 for both the 91 and 533 kev levels.

3. 4. 18   *STUDY OF THE EMISSION OF NEGATIVE ELECTRONS ACCOMPANYING AND ACTIVITIES BY THE COINCIDENCE TECHNIQUE. Maurice Duquesne (College de France, Paris). Ann. Phys. (13), 6: 643-702 (May, June 1961) (In French)

A study is made to extend as far as possible the utilization limits of the coincidence method (β - e$^-$) by working out a geometry and methods adapted to eliminate parasite coincidences. This coincidence technique is then applied to the study of some nuclear physics problems. An e$^-$ spectrum in coincidence with the β radiation was detected for the pure β emitters S-35, P-32, Pm-147, and RaE. The maximum energy of the spectra is in sharp disagreement with the energies fixed by the theory of self-ionization; nevertheless, the total intensity of the phenomena is of the order of magnitude fixed by this theory of self-ionization; nevertheless, the total intensity of the phenomena is of the order of magnitude fixed by this theory and corresponds with the measurements of the intensity of the characteristic x radiation. A similar study was made for the α emitter Po-210 and it was shown that the energy and the intensity of the e$^-$ emitted correspond to the order of magnitude fixed by the theory of self-ionization.

3. 4. 19   GAMMA-GAMMA DIRECTIONAL CORRELATIONS IN Nd-147. Atam P. Arya (Department of Physics, The Pennsylvania State University Park, Pennsylvania). Physical Review 102, 1226, May 1961

ABSTRACT

Directional correlation measurements have been made on the 320- to 92-kev and 280- to 320-kev gamma-ray cascades in Pm-147 following the decay of 11. 1 day Nd-147 with a coincidence scintillation spectrometer using NaI detectors. The observed correlation functions are:

$W(\theta) = 1 - (0.1030 \pm 0.0298) \, P_2(\cos \theta) + (0.0107 \pm 0.0099) \, P_4(\cos \theta)$ and $W(\theta) = 1 + (0.0710 \pm 0.0162) \, P_2(\cos \theta) - (0.0126 \pm 0.0103) \, P_4(\cos \theta)$, respectively, for the two cascades. The energy levels of Pm-147 at ground state, 92 kev, 410 kev, and 690 kev were found to be 7/2+, 7/2+, 7/2+, and 5/2+, respectively. It was found that the 92-kev gamma ray has a mixture of $(95 \pm 2)\%$ M1 and $(5 \pm 2)\%$ E2 with $\delta_{92} +$ (0.229 ± 0.143), the 320 kev gamma ray has a mixture of % M1 with 99% E2 with $\delta_{320} = +9.95 \pm 0.11$, and the 280-kev gamma ray has a mixture of 99% M1 and 1% E2 with $\delta_{280} = 0.11 \pm 0.11$.

Three neodymium samples, in the form of metallic fused chips 99.9% pure, were irradiated at different times in the thermal neutron flux of the Pennsylvania State University Research Reactor for different lengths of time varying from 75 to 130 hrs. Because of the simultaneous production of Nd-149 ($T_{1/2} = 26$ hrs), irradiated samples were allowed to decay from three to six weeks in order to get rid of these short-lived activities. The correlation experiments were started only when the activity left was mainly Nd-147 (11.1 days).

3.4.20   *THE g FACTOR OF THE 92-KEV LEVEL AND OTHER ANGULAR CORRELATION MEASUREMENTS ON Pm-147. E. Bodenstedt, H. J. Korner, F. Frisius, D. Hovestadt, and E. Gerdau (Universitat, Hamburg). Z. Physik 160, 33-46 (1960) (In German)

ABSTRACT

The gyromagnetic ratio of the 92 kev level of Pm-147 was determined by a measurement of the 321 kev-92 kev angular correlation in an external magnetic field of 15,000 gauss. The result ($g = +1.42 \pm 0.20$) implies corrections for the paramagnetism of the 4f-electron shell and for a time dependent attenuation by internal fields. A new determination of the half life of the 92 kev level confirmed the known value. The half life of the 412 kev level was found to be $T_{1/2} \leqslant 5 \cdot 10^{-10}$s. The following angular correlations were measured: 321 kev-92 kev cascade $W(\theta) = 1 - (0.087 \pm 0.008) \cdot P_2 - (0.001 \pm 0.003) \cdot P_4$, 441 kev-92 kev cascade $(W(\theta) = 1 + (0.065 \pm 0.010) \cdot P_4$, 400 kev-92 kev cascade $W(\theta) = 1 - (0.022 \pm 0.008) \cdot P_2 - (0.002 \pm 0.009) \cdot P_4$, 277 kev-92 kev triple cascade $W(\theta) = 1 + (0.0016 \pm 0.0027) \cdot P_2 - (0.002 \pm 0.003) \cdot P_4$, 277 kev-321 kev cascade $W(\theta) = 1 + (0.0117 \pm 0.0025) \cdot P_2 - (0.0067 \pm 0.0033) \cdot P_4$, 120 kev-321 kev cascade $W(\theta) = 1 - (0.029 \pm 0.011) \cdot P_2 - (0.031 \pm 0.012) \cdot P_4$, and 400 kev-198 kev cascade $W(\theta) = 1 - (0.067 \pm 0.009) \cdot P_2 + (0.001 \pm 0.011) \cdot P_4$.

The spins and multipolarities of different gamma transitions are derived from these results.

3.4.21   MEASUREMENT OF g FACTORS OF SEVERAL SHORT LIVED NUCLEAR STATES IN ODD-MASS NUCLEI.   G. Manning and J. D. Rogers (California Institute of Technology, Pasadena, California).   Nuclear Physics 15, 166-186, February 1960

ABSTRACT

((The first portion of the abstract has to do with As-75, Lu-174, and Hf-177 and has been omitted.))   The g-factor of the 91 kev level of Pm-147 has also been studied.   A definite rotation of the angular correlation being observed, computation of the g-factor from the observed data is uncertain because the time dependent attenuation of the gamma-gamma correlation is not known.   The results are $g = (0.9 \pm 0.2)/G_2$.   The effect of the thermomagnetic nature of the rare earth ions on such measurements on this group of nuclei is discussed as appendix.   Other assumptions may be in deducing the g-factor from the observed rotations of the angular correlations are also discussed in this paper.

3.4.22   RESEARCH NOTES, THE DECAY OF Pm-147.   R. J. Jakeways and W. G. Rosser (Physics Department, The University, Exeter).   Proceedings of the Physical Society (London) 74, 478-9, October 1959

((The purpose of the work described in this article was to investigate the possibility that promethium decays via an excited level at 121 kev in Sm-147 using beta gamma coincidence techniques.   The conclusion reached was that the 121 kev level does not arise from the decay of Pm-147.))

A sample of Pm-147 was obtained from the Radio Chemical Center, Amersham, in the form of a solution in 1 normal HCl.   A source was prepared by evaporating a few drops of this solution on a thin mica disc.   The source was covered with a collodion film.

3.4.23   DIRECT DETERMINATION OF THE HALF LIVES OF NINE NUCLIDES.   J. Paul Cali and L. F. Lowe (Cambridge Research Center, U. S. Air Force, Bedford, Massachusetts).   Nucleonics 17, 10, 86-8, October 1959

ABSTRACT

The half lives of nine isotopes have been newly determined by direct measurement after extensive radiochemical purification. These values are compared in the table with previous values frequently quoted in the literature. To insure radiochemical purity extensive chemical procedures were used for each of the elements after its irradiation ((half life determined for Pm-147 was 2.7 ± 0.1 years.))

3.4.24   REFER TO 3.2.16.   HALF LIFE DETERMINATIONS OF SOME RADIONUCLIDES.   Canad. Journ. Phys. 35, 16-20, 1957

3.4.25   APPLICATIONS OF A MULTI-CHANNEL GONIOMETER. Torsten Lindquist and Erik Karlsson, Arkiv for Fysik 12, 519-36, 1957

ABSTRACT

A multi-channel goniometer (MCG) for gamma-gamma angular correlation measurements is described. The apparatus has four channels. Various methods of measurement and a complete treatment of data are given. The MCG has been carefully tested with well-known correlations (Bi-207, Hs-181, and Co-60). As applications the angular correlations of gamma cascades from Ba-131 and Nd-147 have been investigated. Both cases involve forbidden magnetic dipole transitions from the mixing ratios determined in the correlation experiments. It is possible to investigate the strength of forbidden-ness. An upper limit of the g-factor of the 92 kev level in Pm-147 is determined by studying the influence of a magnetic yield on the angular correlation.

((End of Abstract))

The anisotropy of the 320-92 kev cascades in Pm-147 was found to be A = 0.110 ± 0.010 which is large enough for observing an attenuation. The lifetime of the 92 kev level was 3.5×10^{-9} seconds, however, even with a fairly high field, 25,000 gauss, the attenuation was very small: A (25,000 gauss) = -0.094 ± 0.027. Taking the limits of everything into consideration it is possible to give only an upper limit to the g-factor in this case. It was not possible to measure the sign of g.

3.4.26   *CONTRIBUTION AU ETUDE DES PHENOMENES DE
         FREINAGE INTERNE ET D'AUTOIONISATION ASSOCIES
         A LA DESINTEGRATION BETA.   Langevin (Joliot)
         Annules Physique 2, 16, 1957.   Chap. 3 Rayonnemement
         de freinage interne et externe ae S-35 et Pm-147. ((This
         article is in French and no attempt at translation has been
         made.))

3.4.27   INTERNAL BREMSSTRAHLUNG FROM Pr-143 and Pm-
         147.   N. Starfelt and J. Cederlund (Radiation Physics
         Department University of Lund, Lund, Sweden).   Physical
         Review 105, 241-6, January 1957

ABSTRACT

A NaI(Tl) scintillation spectrometer was used for the study of the
spectral distribution of the internal bremsstrahlung from the beta
emitters Pr-143 ($E_{beta-max}$ = 922 kev) and Pm-147 ($E_{beta-max}$ = 226
kev).   Both the shape of the corrected experimental spectrum and the
total yield of internal bremsstrahlung measured per beta decay disagree
with the original Knipp-Uhlenbeck theory and with the improved
version of this theory which takes into account the nuclear coulomb
field.   For Pr-143 the measure bremsstrahlung yield exceeds that of
the Knipp-Uhlenbeck theory by factors of 1.58 (1.48) and 2.56 (1.50)
at 50 and 500 kev, respectively.   The numbers in parentheses refer
to the coulomb corrected theory.   The corresponding factors for Pm-
147 are 1.58 (1.37) and 6.1 (2.54) at 25 and 150 kev, respectively.
The sources were prepared from carrier free Pr-143 and Pm-147
solutions obtained from the Atomic Energy Research Establishment,
Harwell.   The absolute activities of the solutions were measured at
Harwell by four pi counting and were given an accuracy of $\pm$ 2% for
Pr-143 and 5% for Pm-147.   The sources were made on 10 micro-
grams/cm^2 formvar by evaporation with an infrared lamp.   Four
sources with activities ranging from 34 to 156 microcuries activity
and thicknesses between 160 and 600 micrograms/cm^2 and three Pm-
147 sources with activities from 78 microcuries and average thickness-
es between 20 and 200 micrograms/cm^2 were used in the IB measure-
ments.   The fact that all the sources used gave the same spectrum
within the experimental errors of about 5% $\pm$ at low photon energy
strongly supports the assumption that the external bremsstrahlung
emitted from the source was negligible in comparison with the internal
bremsstrahlung ((Figure 2, shows experimental pulse height
distributions and background spectra for 154 microcuries Pr-143 and

465 microcuries Pm-147; Figure 3, shows the total correction factor converting the scintillation pulse height distribution of the internal bremsstrahlung of Pr-143 and Pm-147 into the true photon spectrum; Figure 5, presents a graph of the internal bremsstrahlung from Pm-147; Figure 7, shows a comparison between experimental and theoretical internal bremsstrahlung yield for P-32, F-35, Pr-143 and Pm-147.)) ((Figures 2 through 7 are not presented.))

3.4.28   REFER TO 3.1.7.   DESIGN AND PERFORMANCE OF A THIN MAGNETIC LENS BETA RAY SPECTROMETER. Proceedings of the Indian Acad. Sei. 44A, 111-122, 1956

3.4.29   HALF LIVES OF Ce-144, Co-58, Cr-51, Fe-55, Mn-54, Pm-147, Ru-105, and Sc-46.   R. P. Schuman, M. E. Jones, and Mrs. A. C. Mewherter (Knolls Atomic Power Laboratory, Schenectady, New York).   Journal of Inorganic Nuclear Chemistry 3, 160-163, October 1956

ABSTRACT

Half lives have been obtained for a number of radionuclides by following the decay of purified samples over periods of time as long as six years.   The data were treated by the method of least squares. The half lives are: 284.5 ± 10 days for Ce-144, 71.3 ± 0.2 day for Co-58, 27.8 ± 0.1 day for Cr-51, 2.60 ± 0.02 year for Fe-55, 2.78 ± 5 days for Mn-54, 2.66 ± 0.02 year for Pm-147, 366.6 ± 0.9 day for Ru-106, and 84.1 ± 0.3 day for Sc-46.

((End of Abstract))

The Pm-147 sample was isolated from fission products by a method which separates the rare earths other than cerium from the other fission products and cerium.   Before the decay curves were started the sample had decayed several years so only the long lived rare earth fission products remained.   The only fission products other than Pm-147 that would be present are 73 year Sm-151 which because of the very low energy beta rays would not count under the conditions used and 1.7 year Eu-155 which has a low fission yield, about 1% that of Pm-147.   In calculating the half life no correction was made for the Eu-155 impurity.

3.4.30   PR-P-29 RESEARCH AND DEVELOPMENT, PROGRESS REPORT.   January 1, 1956 to March 31, 1956 (Atomic Energy of Canada Limited, Chalk River Project, Physics Division, Chalk River, Ontario).   Nuclear Physics 1 by J. N. Robson

Section 1.11 Decay of Nd-147 and the level scheme of Pm-147. Through the use of a ring focus beta ray spectrometer, operated at 0.8 resolution, the beta spectra in coincidence with the 532 kev and 690 kev gamma rays have been studied. Preliminary values of the end points of these spectra indicate beta transitions directly to levels at 532 kev and 690 kev in Pm-147. Rutledge, et al (Physics Review 86, 775, 1952) and Hans, et al (Physics Review 97, 1267, 1955) have proposed two differing level schemes for Pm-147. The present work tends to confirm that of Hans with the possible addition of another level to explain the observed results.

3.4.31   *ON THE INTERNAL AND EXTERNAL BREMSSTRAHLUNG OF Pm-147 and Pr-143. Helene Langevin-Joliot. Compt. rend. 241, 1286-8 (1955, November 7 (In French)

The internal bremsstrahlung spectrum of Pm-147, obtained by a scintillation spectrometer in an appropriate arrangement, disagrees with theory in both its shape and intensity. The number of photons reaches 450% of the theoretical value above 60 kev. The first results on Pr-143 also indicate an excess of photons.

3.4.32   THE RELATIVE ABUNDANCES OF NEODYMIUM AND SAMARIUM ISOTOPES IN THE THERMAL NEUTRON FISSION OF U-235 AND U-233. E. A. Melaika, M. J. Parker, J. A. Petruska and R. H. Tomlinson. Canadian Journal of Chemistry 33, 830, 1955

ABSTRACT

The relative fission yields of neodymium and samarium isotopes have been measured with a mass spectrometer for samples of natural uranium and U-233 that have been irradiated with moderated neutrons. The cross sections for neutron capture by Sm-149 and Sm-151 have been determined to be 66,200 $\pm$ 2500 barns and 12,000 barns, respectively, relative to the cross section of a B-10 monitor. The half lives of Pm-147 and Sm-151 have been evaluated to be 2.52 $\pm$ 0.08 year and approximately 93 years, respectively, from samarium fission yield data for samples differing in age by 7 years.

3.4.33   THE BETA RAY ABSORPTION SPECTRUM OF Pm-147 AND ITS APPLICATION TO THICKNESS MEASUREMENT. L. Mandel, B.Sc., Ph.D., A. Inst.P. (Central Instrumentation Imperial Chemical Industries Limited, Welwyn). British Journal of Applied Physics 5, 287-9, August 1954

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ABSTRACT

The absorption in aluminum of the beta rays from Pm-147 has been measured and found to be nearly exponential with an absorption length of 6.78 mg/cm^2 ± 3%. Curves are given which relate the measuring accuracy with absorber thickness in rapid response beta ray gages using Pm-147 and Tl-204 as sources. These show that under the same conditions the use of Pm-147 leads to greater accuracy at thickness measurement by a factor of 4.

((End of Abstract))

The source for these measurements was supplied by the Radio Chemical Center, Amersham and consisted of an evaporated solution of Pm-147 in hydrogen chloride of approximately 1 mc strength covering an area of about 1 cm^2. ((Figure 2, not reproduced here, presents a comparison of the absorption spectra of Pm-147 and Tl-204.))

3.4.34   DETERMINATION OF THE HALF LIVES OF SOME MAGNETIC DIPOLE GAMMA RAY TRANSITIONS. R. L. Graham and R. E. Bell, Canadian Journal of Physics 31, 377, 1953

ABSTRACT

A number of magnetic dipole gamma ray transitions have been studied using a coincidence circuit of short resolving time, a two lens single gamma ray spectrometer, a pair of lens spectrometers placed end to end with coincidence counting of the focused radiations from a single source, and a scintillation spectrometer. Life times have been measured using the delayed coincidence method and where feasible conversion coefficients and K/L ratios obtained. Comparison is made with theoretical estimates of the life time-energy relation for M-1 gamma ray transitions. The net results are as follows: ((Although several isotopes are mentioned only that information for Pm-147 is given)) E (kev), 91.5; half life (seconds), (2.44 ± 0.08) x 10^{-9}; K-1 ratio, exp 7.3, M-1 7.7 E-2 0.5; alpha, exp 1.8, M-1, 1.9; total alpha 2.2.

3.4.35   IDENTIFICATION AND CHARACTERISTICS OF APPROXIMATE FOUR YEAR Pm-147, PAPER 192. J. A. Marinsky and L. E. Glendenin, Radio Chemical Studies, The Fission Products, Book 2, part V, papers 53-199, McGraw-Hill Book Company, Inc. 1951

ABSTRACT

A detailed study has been made of the long lived isotope of promethium that occurs in fission. The separation and identification of this activity as an isotope of promethium was achieved by the Amberlite (ion exchange) resin absorption elution method. Its decay is characterized by a 0.20 Mev beta ray. No gamma ray is observed. An apparent daughter relationship has been shown to exist between the 11 day Nd and the long lived promethium. The fission yield of this chain is 2.6 ± 0.2%. A mass of 147 has been assigned the chain by mass spectroscopy. The half life of the long lived promethium activity has been calculated as 4.8 years from its observed growth from 11 day Nd but as 4.4 years from the amount of activity formed in fission ((using the fission yield of the 11 day Nd parent)).

3.4.36   ABSORPTION AND EMISSION SPECTRA OF PROMETHIUM.
William F. Meggers, Bourdon F. Scribner and William R. Bozman, Journal of Research of the National Bureau of Standards, Vol. 46, No. 2, 85-98, February 1951, Research Paper 2179.

ABSTRACT

Five milligrams of Pm-147 separated from fission products at the Oak Ridge National Laboratory were loaned by the United States Atomic Energy Commission for this investigation. The absorption spectrum of this sample in solution was plotted between 2500 and 10000 angstroms. The principal bands having wavelengths 494.5, 548.5, 568.0, 685.5, 735.5 millimicrons (± 0.5 millimicrons). Small portions of the sample were dried on copper electrodes employed in photographing alternating current arc and spark spectra with a concave grating of 22 foot radius. Excepting Sm, into which Pm decays, no other rare earths could be detected in this sample, but common chemical contaminants were troublesome. Between 2200 and 6900 angstroms the wavelengths and relative intensities of more than 2200 new spectral lines were determined, but it is not possible to differentiate Pm I and Pm II lines with the light sources employed. The strongest Pm lines have wavelengths 3892.16, 3910.26, 3919.09, 3957.74, and 3998.96 ± 0.02 angstroms. Hyperfine structure is suspected in some Pm lines indicating that the nuclei of Pm-147 atoms disposes mechanical and magnetic moments. Confirming the findings of the Oak Ridge National Laboratory, both the absorption and emission spectrum identify this fission product as a new element of rare earth

type.   They provide positive proof that the long sought element with atomic number 61 has been discovered.

((End of Abstract))

((The balance of this article is concerned with the optical spectra of Pm-147 and is not described here.))

3. 4. 37   LOW ENERGY BETA RAY SPECTRA.   Pm-147, S-35.

L. M. Langer, J. W. Motz and H. C. Price, Jr.
(Department of Physics,Indiana University, Bloomington, Indiana).
Physical Review 77, 798-805, March 1950

ABSTRACT

The beta spectra of S-35 and Pm-147 have been measured in order to study further the nature of any low energy deviation from the Fermi theory of beta decay.   Measurements were made within relatively uniform sources in both the 40 centimeter radius of curvature spectrometer and also in a small 180° focusing Helmholtz coil spectrometer designed specifically for low energy spectra.   The thinnest sources were less than ten micrograms/cm^2.   Using zapon counter windows ranging from 1. 5 to 3 micrograms/cm^2 and also a windowless counter technique, Fermi plots were obtained which showed how the measure distribution of particles at low energy depends on both source and counter window thickness.   Favorable experimental conditions yielded a straight line Fermi plot for Pm-147 above 8 kev.   Less favorable conditions resulted in a straight line plot for S-35 down to at least 50 kev.   Thus, S-35, which is allowed, and Pm-147, which is probably once forbidden, are found to have spectra of the allowed shape.   It is concluded that under very favorable experimental conditions there is probably no real disagreement between the observed momentum distribution and that predicted for an allowed transition by the Fermi theory.   On the basis of an improved calibration the following end points are obtained: Pm-147, 223.2 ± 0.5 kev and S-35, 167.0 ± 0.5 kev.

((End of Abstract))

In view of the conflicting reports in the literature on the effect of source thickness, we made a study of auto-radiographs of sources prepared from chemical solutions.   By this technique it was found that, in general, such sources, though appearing uniform, may in

many cases have variations of intensity of as much as 100 fold.   Under
these circumstances, the average source thickness as reported by
various investigators does not have much meaning.   We are as yet
unable to deposit completely uniform sources from chemical solution.
Our best technique consists of wetting the portion of the backing foil on
which the source is to be placed with one drop of 5% solution of Lily
insulin, 40 units per cc in water.   A drop of radioactive solution
applied any place in this area will spread over the entire region
defined by the insulin.   Fairly uniform sources are easily made on
larger areas by covering the region with narrow insulin lines and
putting a small drop of liquid source on each.   Extremely uniform
sources can, if activity permits, be successfully prepared by thermal
evaporation in vacuum.

3.4.38   LOW ENERGY BETA RAY SPECTRA PROMETHIUM-147
            AND SULPHUR-35.   H. C. Price, Jr., J. Motz, and
            L. M. Langer (Indiana University).   Physical Review 77,
            744, 1950

ABSTRACT

The beta spectra of S-35 and Pm-147 have been measured in an
attempt to study further the nature of the low energy deviation from
the Fermi previously reported.   Fermi plots were obtained which for
Pm-147 were straight down to 8 kev.   The end point of Pm-147 was
found to be 223.2 ± 0.5 kev.

3.4.39   THE BETA SPECTRA OF Cs-137, Y-91, Pm-147, Ru-106,
            Sm-151, P-32, and Pm-170.   Harold M. Agnew (Institute
            of Nuclear Studies, University of Chicago, Chicago,
            Illinois).   Physical Review 77, 655-60, March 1950

((Abstract for this article is found as reference 3.3.48 in Cs-137
section.))

((Promethium-147 half life 3.7 years: ift = 4.01×10^7; Sources of
promethium weighing less than 0.05 mg/cm^2 were prepared from
material obtained from Oak Ridge.))

3.4.40   THE BETA SPECTRUM OF Pm-147.   L. Lidowsky, P.
            Macklin and C. S. Wu (Pupin Physics Laboratories,
            Columbia University, New York, New York).   Physical
            Review 76, 1888-9, December 1949

ABSTRACT

High specific activity Pm-147 has recently become available from the Isotopes Division of the AEC at Oak Ridge where it is made as a fission product. This high specific activity material, when used in the high transmission solenoidal focusing beta ray spectrometer, makes it possible to investigate its beta spectrum when using sources less than 30 micrograms/cm^2 thick. The Pm-147 received as Pm-147 Cl$_3$ in 0.1 normal HCl was evaporated to dryness and then re-dissolved in distilled water to which a small amount of wetting agent (Antorox) was added. A 0.01 milliliter drop placed on a collodion backing approximately 10 micrograms/cm^2 formed a uniform source spread over a circular area of about 0.5 cm^2 (an end point for Pm-147 of 227 $\pm$ 1 kev was obtained). The plot was straight from the end point down to at least 35 kev. Below this energy the curve deviated slightly upward and then again downward in a manner that could be attributed to finite source thickness end window absorption. The above end point in conjunction with the reported value of the half life (3.7 years) yielded a ft value for the transition of 1.2 times 10^7 which foreign element with a Z of 61 indicates a first or second forbidden spectrum. Although the curve has an allowed shape, this is not a contradiction since, for certain interactions, a forbidden transition may exhibit allowed shape.

3.4.41   THE K SPECTRA OF ELEMENT 61.   L. E. Burkhar, W. F. Peed, E. J. Spitzer (Clinton Engineering Works, Carbide and Carbon Chemicals Corporation, Oak Ridge, Tennessee).   Physical Review 75, 86-9, 1949

ABSTRACT

The K alpha 1, K alpha 2, K beta 1 and K beta 2 lines of the X-ray spectra of element 61 were obtained from 1.5 mg of sample of the chloride salt. The sample was fused on a copper target and bombarded with electrons from a 70 kev source. Wavelength measurements were made from a microphotometer tracing of the film. After one exposure of the sample neodymium and samarium were added to the spectrum of the three elements was recorded to show the position of element 61 in the periodic table.

3.4.42   MASS SPECTROGRAPHIC MASS ASSIGNMENT OF RADIOACTIVE ISOTOPES.   Richard J. Hayden (Metallurgical Laboratory University of Chicago, Chicago, Illinois). Phys. Rev. 74, 650, Sept. 1948

ABSTRACT

((Characteristics of positive ion emission for various compounds on a
tungsten filament are cited.   Methods of analysis of mixtures of radio-
active isotopes by mass spectrograph are described.   The following
mass assignments are made.   Only those for elements of interest are
given, 3. 7 year element 61, 147; 21 year strontium, 90.))

3. 4. 43   THE CHEMICAL IDENTIFICATION OF RADIOISOTOPES
           OF NEODYMIUM AND ELEMENT 61.   J. A. Marinsky,
           L. E. Glendenen and C. D. Coryell, Journal of the
           American Society 69, 2781, 1947

((Article describes the chemical identification of Pm-147.))

3. 4. 44   UCRL-10245.   INVESTIGATION OF ELECTRONIC AND
           NUCLEAR PROPERTIES OF SOME RARE EARTH
           ISOTOPES.   (University of California, Ernest O.
           Lawrence Radiation Laboratory). Page 22, Section A

Promethium, atomic number 61 has no stable isotopes, is a fission
product, and has a half life of 2. 6 years.   Its beta spectrum has been
measured accurately, and although first forbidden exhibits the
allowed shape, there is evidence of a gamma spectrum.

POLONIUM-210

HALF LIFE

    138.4005 ± 0.0051 days   Ref. 3.5.33 Phys. Rev. 96,
                                    719-721, Nov. 1954

    Gamma Transition 10^{-9} sec   Ref. 3.5.39 Phys. Rev. 85,
                                    944-5, Nov. 1952

ENERGY LEVELS AND DECAY SCHEME

    Po-210 $\xrightarrow[100\%]{\text{ALPHA}}$ Pb-206

    ALPHA - 5.30493 ± 0.006   Ref. 3.5.8 Helv. Phys. Acta
                Mev   34, 960-76, 1961

    GAMMA - 0.800 ± 0.006   Ref. 3.5.13 Phys. Rev. 81,
                Mev   523-6, Feb. 1961

       (Transition from first excited state of Pb-206
       to the ground state)

    Probability of branching to   Ref. 3.5.26 J. Exptl. Teoret
    the first excited level of Pb- Phys. USSR 31, 174-7,
    206 = (1.2 ± 0.2) 10^{-5} Aug. 1956
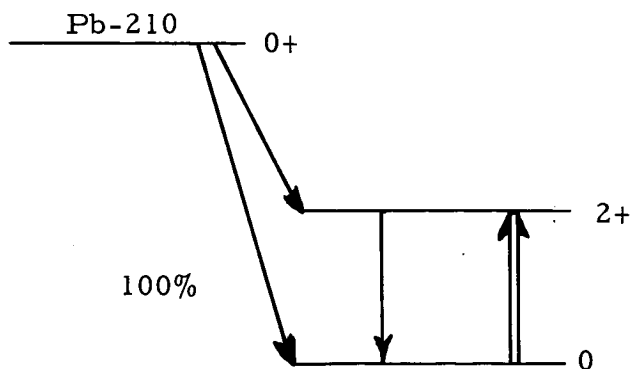
Rev. Mod.
Phys, Vol.
30, No. 2,
Pt. II,
Apr. 1958

3.5.1   REFER TO 3.6.3.   ALPHA SOURCES FOR LOW THRUST
         TASKS IN SPACE.   International Journal of Applied
         Radiation and Isotopes 15, 127-31, March 1964.

3.5.2   THE MECHANISM OF ALPHA-DECAY, AND THE
         REDUCED LEVEL WIDTHS OF Po-210 AND Po-212.
         K. B. Baktybaev and B. M. Bukat. Izv. Akad. Nauk SSSR,
         Ser. Fiz, 27:1297-1304 (Oct. 1963)

ABSTRACT

The simple model of the penetration of a potential barrier by an alpha
particle can be modified by introducing the reduced with γ_L; whose
square characterizes the probability for formation of an alpha group
within the nucleus: $\gamma_L = (2\lambda_L/h)P_L$.   Here λ is the decay constant
for the emission of an alpha particle with a definite orbital moment L,
and P_L is the barrier penetrability.   The value of γ_L is determined
by the behavior of the internal wave function of the nucleus, and the
probability of alpha decay can be related to the nuclear structure.   The
reduced widths for a decay are calculated for Po-210 and Po-212 by
taking into account the role of correlations associated with residual
pair interactions in the nucleus.   A number of alpha transitions to
excited states are strongly forbidden due to the low probability of a
particle formation in the nucleus.   Values of γ^2_{pure}, calculated on
the assumption that the nuclear states are pure shell states, are
compared with values of γ^2_{mixed}, where the residual pair interactions
lead to mixed configurations.   It is shown that the probability of alpha
decay in Po-210 and Po-212 is strongly dependent on tunneling effect.

3.5.3   MEASUREMENT OF THE LEAD M PHOTON INTENSITY
         IN Po-210 DECAY; A FURTHER GROSS INADEQUACY OF
         THE THEORY.   William Rubinson (Department of
         Chemistry, Brookhaven National Laboratory, Upton, New
         York).   Physical Review 130, 2011-202, June 1963. ((See
         also BNL-6166 in this section.   The present article is by
         and large an updated version of that report.))

ABSTRACT

The probability that a Pb M photon is emitted in Po-210 decay is 0.91
($\pm$ 15%) x 10^{-3} photons per alpha as measured by means of a propor-
tional counter and pulse height analyzer.   This value is in gross
disagreement with theoretical estimates.   A Pb M spectrum from Po-

210 decay shows definite differences from a conventional Pb M spectrum, indicating considerable injection of higher shell electrons in the Po-210 decay act. In particular the spectrum from Po-210 contains a 3.7 kev component whose intensity is about 4% of the total spectral intensity and whose energy is consistent with the allowed but hitherto unreported transition $M_{2,3}$. The theory of electron ejection in alpha decay is reviewed and previously calculations of ejection probabilities are extended to include ejection to bound states. The estimates of K, L, and M photon yields in this theory are orders of magnitude lower than the measured yields. Possible sources of the discrepancy are discussed.

((End of Abstract))

About 30 millicuries of Po-210 were obtained from the Monsanto Chemical Company as an invisible quantity of the dry nitrate. The supplier stated it to assay at 99.9% Po-210. Possible impurities being Bi and Pt. Without further purification the Po-210 was taken up in three milliliters of a 2.4 normal nitric acid solution that had been prepared with triply distilled water. This constituted our Po-210 stock solution which assayed by the method of dilution and alpha counting proved to have a specific activity of $1.956 \times 10^{10} \pm 2\%$ disintegrations per minute per milliliter 8.81 millicuries per milliliter, a value of about 1% higher than that computed from the supplier's states assay. In order to test for possible effects of source thickness, sources of strength ranging over a factor of 10 were prepared namely with alequot volumes 5, 10, 25, and 50 lambda (0.044 to 0.44 millicuries) for each of these strengths at least two sources were made. The measured X-ray intensities proved to be independent of source strengths over this range.

3.5.4   LIFETIMES OF THE 246 and 46.7 KEV TRANSITIONS IN POLONIUM-210. E. G. Funk, Jr., H. J. Prask, F. Schima, J. McNulty, and J. W. Mihelich (University of Notre Dame, Notre Dame, Indiana). Physical Review 129, 757-9, January 1963

ABSTRACT

The half lives of the 1431 and 1478 kev levels in Po-210 have been measured. The experimental values being 1.8 ± 0.2 nsec and 29 ± 6 nsec, respectively. These levels are depopulated by E2 transitions of 246 and 46.7 kev whose transition probabilities are approximately three times greater than the single part nickel estimates. One of the

most sensitive tests of nuclear models is the determination of gamma ray transition life times. We have undertaken an extensive study of the levels of Po-210 as populated by the electron capture decay of 8.3 hour At-210. This nucleus is of particular interest since it has a closed neutron shell (n = 126) and 2 protons outside of the closed proton shell at Z = 82.

3.5.5 ABSOLUTE PRECISION DETERMINATION OF SEVERAL RESONANCE THRESHOLD ENERGIES AND THE ALPHA PARTICLE ENERGY OF Po-210, PART II. A. Rytz, H. H. Staub, H. Winkler and W. Zych (Physik Institut der Universtitat, Zurich). Helv. Phys. Acta 35, 341-50, 1962

In Part I of this paper,** we described absolute measurements of the thresholds of the reactions Li-7 (p, n) Be-7 and T (p, n) He-3 and the alpha particle energy of Po-210 with a semicircular magnetic spectrometer. The same apparatus and method has been used for the remeasuring absolute energy values of the reactions A-127 (p, gamma) Si-28 at 992 kev and F-19 (p, gamma) O-16 at 872 kev both of which were used as calibration standards. ((The balance of this article does not contain any new information on the alpha particle energy of Po-210. The article is referenced here primarily to provide continuity with Part I of this work.))

**Helv. Phys. Acta 34, 960-76, 1961

3.5.6 COMPARISON OF ALPHA PARTICLE ENERGIES FROM Po-210 AND Po-214 AND THE ENERGY OF Po-210 ALPHA PARTICLES. Cornelius B. Brown (University of Notre Dame, Notre Dame, Indiana). Physical Review 124, 1139-42, May 1962

ABSTRACT

The energies of alpha particles emitted by Po-210 and Po-214 were compared with a broad range spectrograph. Techniques were the same as those used in recent comparison of the Po-210 alpha particle energy with the Li-7 (p, n) Be-7 reaction threshold energy. The result agrees with other measurements and thus the discrepancy between Po-210 alpha particle energies measured against the Briggs value for Po-214 and the Po-210 alpha particle energy measured absolutely or against the Li-7 (p, n) Be-7 threshold remains. If Rytz's recent absolute value for the Po-210 energy is used**, the discrepancy

disappears.   A summary of all measurements show that the energy of alpha particles from Po-210 is very close to 5. 3045 Mev.

**Ref. 3. 5. 8.   Helv. Phys. Acta 34, 960-76, 1961

3. 5. 7   MASS NUMBER ASSIGNMENTS AND ALPHA ACTIVITIES
             OF LIGHT POLONIUM ISOTOPES.   Wilhelm Forsling and
             Torsten Alvater, Arkiv fur Physik 19, 353-68, 1961

ABSTRACT

Light polonium isotopes have been produced mainly by utilizing heavy ion bombardments.   Mass number assignments of these nuclides have been made by use of an electromagnetic isotope separator.   The alpha activities of Po-198, 199, 200, 201, 202, 203, 204, 205, 206, 208, and 210, were studied in this work.

((End of Abstract))

The samples of Po-210 used in the present experiments were obtained from small glass tubes which had been filled with radon and used in therapy at the Institute of Radio Physics in Stockholm.   As is well known, Rn-222 decays to Po-210 which is found in the deposit on the walls of such tubes.   After about three years the Po-210 activity had reached its equilibrium.   The active deposit was extracted from the radon bulbs ((and)) the Po-210 samples were then made by electro-chemical replacement onto silver foils in 0. 4 m nitric acid.   ((As a result of the work described in this article, the alpha particle energy of Po-210 is determined to be 5. 30 ± 0. 02 Mev.))

3. 5. 8   ABSOLUTE PRECISION DETERMINATION OF SEVERAL
             RESONANCE THRESHOLD ENERGIES AND THE ALPHA
             PARTICLE ENERGY OF Po-210, PART I.   A. Rytz,
             H. H. Staub, and H. Winkler (Physik Institut der
             Universitat, Zurich).   Helv. Phys. Acta 34, 960-76, 1961

ABSTRACT

Po-210 is still used extensively as an energy standard despite its well known detrimental properties.   It therefore seems desirable to make a new absolute measurement of this energy value with our spectrometer. The quality of every Po-210 alpha measurement depends to a high degree on the source properties.   The most successful procedure

seems to consist in deposition by volatilization in vacuum on a polished tantalum surface. Our source has been prepared by the Laboratoire de l'Amimant Permanant at Orsay, France, where this technique has been developed by R. J. Walen. The polonium had been deposited on only one narrow side (8 x 0.3 mm^2) of a piece of tantalum 10 x 8 x 0.3 mm which had been polished previously. ((As a result of the work described in this article, the Po-210 alpha particle energy is determined to be 5304.93 ± 0.60 kev.))

3.5.9   COMPARISON OF ALPHA PARTICLE ENERGIES FROM VARIOUS POLONIUM-210 SOURCES. C. P. Brown (University of Notre Dame, Notre Dame, Indiana) and T. A. Eastwood (Atomic Energy of Canada Limited, Chalk River, Canada). Physical Review 124, 1494-6, December 1961

ABSTRACT

A comparison of the energies of alpha particles from six different Po-210 sources was made with the same broad range spectrograph used for a recent comparison of the Po-210 alpha particle energy with the Li-7 (p, n) Be-7 threshold energy. The sources were prepared by different techniques and some were on flat backings whereas others were on cylindrical backings. It is concluded that the discrepancies in most recent measurements of the alpha energy does not arise from source preparation techniques but the lower values of the older measurements may have been caused by source aging. ((This report was part of a project whose goal was to eliminate the variable of source condition. The energy of alpha particles from source made by one person by one technique were measured in different laboratories and compared with results obtained using sources made by the various techniques used in those laboratories.))

3.5.10   ALPHA PARTICLE REDUCED WIDTHS IN HEAVY NUCLEI. Kichinosuke Harada (Nuclear Physics Department, Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken). Progress in Theoretical Physics 26, 5, 667-79, November 1961

ABSTRACT

The alpha particle reduced widths (Ro^2) for the ground state in Po-210 and Po-212 are calculated on the basis of the nuclear shell model. The

calculations are made taking the boundary condition in an approximate way into consideration. The effects of the consideration mixing of the parent and daughter nucleus wave functions on $\text{gamma}^2_{\text{alpha}}$ are examined and it is found that they give quite large contributions to $\text{gamma}^2_{\text{alpha}}$. Some features of the distortion of the two nucleon wave functions arising from the configuration mixing are discussed graphically. It is shown that the wave function of relative motion with the mixing of the level which is lowered from the upper band by spin orbit force would correspond to the bound electron pair in the superconducting metals. Although there are some unavoidable uncertainties in the course of the calculation it is concluded that wave functions derived by conventional shell model calculations can explain the major part of the experimental values of $\text{gamma}^2_{\text{alpha}}$. ((This article is entirely theoretical in nature.))

3.5.11   *STUDY OF THE AUGER L ELECTRONS FOLLOWING THE AUTOIONIZATION PHENOMENON IN Po. A. Juillard and A. Moussa (centre d'Etudes Nucleaires, Grenoble, France). J. Phys. Radium 22:677-9 (Oct. 1961) (In French)

A study is carried out of the rearrangement Auger L electrons following the autoionization process after disintegration of Po-210. Experimental results are between 1.3×10^{-3} to 2.5×10^{-3} Auger L electrons per disintegration. These results are compared with measurements of rearrangement X-K and X-L photons and with the theoretical value.

3.5.12   ABSOLUTE MEASUREMENT OF A SET OF ENERGY CALIBRATION STANDARDS. E. H. Beckner, R. L. Bramblett and G. C. Phillips (Price University, Houston, Texas), and T. A. Eastwood (Atomic Energy of Canada Limited, Chalk River, Ontario, Canada). Physical Review 123, 2100, September 1961

ABSTRACT

A 180° magnetic spectrometer has been employed to measure the energy of several neutron thresholds and gamma ray resonances as well as the energy of the alpha particles emitted by Po-210. The primary reason for performing these experiments was to obtain a set of energy standards with consistent experimental techniques for all the measurements. The neutron thresholds studied were Li-7, (p, n) Be-7; B-11 (p, n) C-11; C-13 (p, n) N-13; and F-19 (p, n) Ne-19. The gamma ray residences at 872 kev in F-19 (p, alpha-gamma) 0-16 and

992 kev in Al-27 (p, gamma) Si-28 were observed.   The same
instrument used to make energy measurements in these experiments
was also employed to determine the energy of the alpha particles
emitted by Po-210.

((End of Abstract))

The sources used for these experiments were prepared by currentless
electrodeposition on pure silver foils using two slightly different
techniques.   Nine sources were prepared by one of the authors by
dipping the source backings into the polonium solution for periods of
from 2 to 10 minutes.   These sources were used immediately after
preparation in order to avoid the familiar problem of polonium
diffusion into the backing.   Several other sources were prepared by
the second author by a somewhat different technique.   These latter
sources were prepared by placing a small amount of the polonium
solution directly on the surface of the source backings.   These sources
were also used immediately after their preparation.   In no case were
sources more than 6 hours old employed in these measurements.
Sources of various activities were employed by using the source
preparation time to range from 2 to 20 minutes.

3.5.13   GAMMA RADIATION FROM Pb-206.   D. E. Alburger,
            and G. Friedlander (Brookhaven National Laboratory,
            Upton, New York).   Physical Review 81, 523-6,
            February 1961

ABSTRACT

Gamma rays accompanying the electron capture decay of 6.4 day, Bi-
406 and the alpha decay of 138 day Po-210 have been observed by
measurement of internal conversion electrons and photoelectrons with
a lens spectrometer.   The bismuth activity showed the resolved lines
corresponding to the gamma rays of 182, 234, 260, 341, 470, 505,
536, 590, 803, 880, 889, 1020, 1097, and 1720 kev.   A thin Po-210
source of 480 mc alpha particle strength was found to emit gamma
rays of 800 $\pm$ 6 kev energy which yielded K and L internal conversion
lines in the ratio of 3.7 $\pm$ 0.5 to 1.   The 803 kev gamma ray observed
in both the Bi-206 and Po-210 activities is identified with a transition
from a first excited state of Pb-206 to the ground state.

((End of Abstract))

The Po-210 source was specifically prepared for this work by the AEC. It consisted of carrier free polonium deposited on a nickel disc over an area 0.5 centimeter in diameter and covered with 0.2 mil gold foil (about 10 mg/cm^2) for the purpose of reducing the spread of contamination. The foil had been clamped with a metal ring and sealed at the outer edges with a vacuum evaporated coating. At the time of fabrication, the alpha particle strength was 478 millicuries and from this the thickness of the source is estimated to be about 0.5 mg/cm^2.

3.5.14   BNL-6166.   THE LEAD X-RAYS THAT ACCOMPANY POLONIUM 210 DECAY.   MEASUREMENT OF THE M PHOTON YIELD AND THEORY.   William Rubinson, Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York.   1960. 46 pgs.

The probability that the lead M photon is emitted in the alpha decay of Po-210 atom is 0.91 ± 15% x 10^{-3} photons per alpha, as measured by means of a proportional counter and pulse height analyzer. The value is in gross disagreement with theoretical estimates. A lead M spectrum from Po-210 decay shows definite differences from a conventional spectrum, indicating extensive ejection of the outermost electrons in the decay act. In particular, the spectrum from Po-210 contains a 3.7 kev line whose intensity is about 4% of the total spectral intensity, and whose energy is consistent with the allowed but hitherto unreported transition $M_1O_{2,3}$.

The theory of electron ejection in alpha decay is reworked and the results are compared with the measured values of K, L, and M ejections in Po-210 decay. It is concluded that the apparent agreement between measured probability of K ejection and the theoretical calculations of Midgal and of Schaefer is fortuitous and that for K as well as for L ejections there is an order of magnitude difference between theory and experiment. And too, the failure of the theory can be ascribed in a large part to the unjustifiable set of hydrogenic wave functions.

3.5.15   MEASUREMENT OF THE ENERGY OF THE WEAK GROUP AND THE ALPHA SPECTRA OF Po-210.   T. Fenyes (Institute for Experimental Physics, Debrecen, Hungary). Nuclear Physics 16, 529-533, 1960

ABSTRACT

The nuclear spectrum of Po-210 was examined with a scintillation alpha-gamma coincidence equipment combined with an electrostatic

alpha spectrometer accepting 5. 3054 ± 0. 0010 Mev (absolute v) as the value for the kinetic energy of the main group, that of the weak group was found to be 4. 525 ± 0. 005 Mev.   As is well known Po-210 emits mostly alpha particles of 5. 3 Mev kinetic energy but it has also some gamma radiation of very low intensity.   The gamma spectrum has been investigated by a number of authors.   The measurements have revealed that the gamma radiation of Po-210 consists of a single line of about 800 kev.   No other lines have been observed, at any rate, not in the interval between 25 kev and 2. 5 Mev.   The aim of this investigation was the precise determination of the energy ratio between the weak and main alpha groups through direct alpha spectroscopy.   The Po-210 source was prepared ((by the method of)) volatilization and concentration of polonium in a hydrogen stream.

3. 5. 16   COMPARISON OF Po-210 ALPHA PARTICLE ENERGY WITH THE Li-7 (p, n) Be-7 REACTION THRESHOLD ENERGY.   C. P. Browne, J. A. Galey, J. R. Erskine and K. L. Walsh (Department of Physics, University of Notre Dame, Notre Dame, Indiana).   Physical Review 120, 905-13, November 1960

ABSTRACT

Recent absolute measurements of the Po-210 alpha particle energy disagree with the older value used as the standard for many nuclear reaction energy measurements.   A new comparison with the Li-7 (p, n) Be-7 reaction threshold energy was made using the Notre Dame electrostatic accelerator and broad range spectrograph.   Four separate methods of comparison were used.   In the first three, the threshold was run and then protons or deuterons were scattered from appropriate targets so that the scattered group was recorded on the spectrograph plate near the alpha group from a source placed at the target position.   First the spectrograph, and second the beam analyzer, were used to compare particle momenta.   Third, with both fields held constant after the threshold was run with the molecular beam, deuterons were scattered giving particles of the same B_p as the alphas.   In the fourth method several reaction energies that were precisely known in terms of the Li-7 (p, n) Be-7 reaction threshold energy were measured in terms of the Po-210 alpha particle energy.   These were the Mg-24 (d, d') Mg-24* reaction to the first excited state of Mg-24 and the N-14 (d, p) N-15 reaction leading to three excited states of N-15.   The four measurements agree and give 5. 3086 ± 0. 003 Mev for Po-210 alpha particle energy based on 1. 8811 Mev for the Li-7 (p, n) Be-7 reaction threshold energy.

3.5.17   *ABSOLUTE MEASUREMENT OF SOME ALPHA
          ENERGIES.   Albrecht Rytz.   Compt. rend. 250, 3156-8
          (1960) May 9   (In French)

The absolute energies of the radiation of Po-210, Po-212, Po-214,
Bi-211, and Bi-212 were determined by magnetic spectrography with
field controlled by nuclear resonance and absolute measurement of
the trajectory lengths.

3.5.18   GAMMA RAYS FROM A POLONIUM OXIDE 18 NEUTRON
          SOURCE.   E. M. Tsenter, A. G. Khabakhpashev and I.
          A. Pirkin, J. Exptl. Theoret. Phys. 37, 1133-1134,
          October 1959 ((translated in Soviet Physics J. E. Tepee
          37, 4 April 1960))

ABSTRACT

In a previous paper it has been shown that a Po O neutron source the
(alpha, n) reaction operates on the isotope O-18.   The neutrons yielded
by the reaction O-18 (alpha, n) Ne-21 are accompanied by 0.35 Mev
gamma rays with a relative intensity of $30 \pm 10\%$.   The Po O-18
spectrum contains a certain number of pulses with energies up to 2.8
Mev.   Some of these are evidently due to neutrons registered by the
sodium iodide crystals.   Others are possibly due to hard gamma rays
which could not be detected in the course of the measurements because
of low intensity.   The intensity of the 0.35 Mev and 1.38 Mev gamma
lines were determined from the areas under the full energy peaks.
The crystal counting efficiency in a ratio of the area under a photopeak
to that under the entire spectral curve was taken from other references.
The intensity of the 0.35 Mev line relative to the neutron yield was
found to be $45 \pm 5\%$.   The intensity of the 1.38 Mev line was 10 ± 2.
Upper limits for the relative intensity for the 1.73 Mev gamma line
and the 2.84 Mev line were determined from the complete gamma
spectrum of the Po-O-18 source.   The upper limit was 1% for the
1.73 Mev line and 2% for the 2.84 Mev line.

3.5.19   *ON THE NUCLEAR SHELL STRUCTURE THEORY.
          Ming Yu (Inst. of Nuclear Energy, Academy of Sciences).
          Wu Li Hsueh Pao 15, 420-39/ (1959) August (In Chinese)

The problems of nucleon-nucleon interactions outside saturated shells
are analyzed by perturbation methods.   The method of wave expansion
was developed for calculating Pb-206, Po-210, and Bi-210 energy

spectra. The results are in good agreement with experimental data. It was shown that nuclear energy spectra are determined by S-wave interactions. The interaction intensity is in agreement with the effective radius of nuclear force action and scattering path and does not depend on the shape of the nuclear force. In special cases P-wave interactions play an important part. The analysis showed that excluding the S-wave interactions the repulsive force of $^3P_0$ wave interactions is the strongest force between two nucleons.

3.5.20 *POLONIUM-210 AS A STANDARD FOR GAMMA RADIATION. Genevieve Bastin-Schoffier and Robert J. Walen, Compt. rend, 247, 2333-5 (1958) Dec. 22 (In French)

The alpha magnetic structure of Po-210 was studied to determine the branching ratio in the fine structure. The ratio of the weak alpha to the strong alpha emission was determined, and the gamma/alpha ratio was found to be 1.006×10^{-5}.

3.5.21 THE EMISSION OF LONG RANGE ALPHA PARTICLES WITH E_{alpha} OF 10 MEV BY Pu-239 and Po-210. V. N. Andreev and S. M. Sirotkin. Isv. Akad. Nauk SSSR, Ser. Fiz. 27:1250-2 (Oct. 1958)

Ader in the J. Phys. et Radium 15:60, 191 (1954) and 17:45 (1956) observed the emission of 10^{-6} to 10^{-8} long range alpha particles for each alpha decay. These alpha particles have a range of 100 to 300 u in photoemulsions (12 to 25 Mev), and are thought to be due to spontaneous or forced triple fission. A specially constructed ionization chamber was set up to count the long range alpha particles in the presence of ordinary alpha radiation. A 10 mg sample of Pu-239 was deposited on an aluminum disc having a density of 0.5 mg/cm^2, and was covered with an aluminum foil 28 u thick. The 70 ug sample of Po-210 was electrodeposited on a nickel plate, and was covered with a tinfoil 15.3 u thick and with two aluminum foils having a total thickness of 14.4 u in order to avoid the interference from an (a, p) reaction on the aluminum. The total count rates were found to be 0.55 ± 0.09 counts/hr for the Pu-239 sample, and 1.0 ± 0.1 counts/hr for the Po-210 sample for 10 to 15 Mev alpha particles. It was concluded that Pu-239 emits 10^{-10} long range alpha particles per alpha decay, and Po-210 emits 7×10^{-13} long range alpha particles per alpha decay at the 95% confidence level.

3.5.22   ENERGY LEVELS OF POLONIUM-210.   R. W. Hoff and
          J. M. Hollander (University of California Radiation
          Laboratory, Livermore and Berkeley, California).
          Physical Review 109, 447-56, January 1958

ABSTRACT

The energy levels of Po-210 have been studied as populated by the
electron capturing decay of At-210 and experimental level scheme has
been constructed by using data obtained by conversion electron and
gamma ray measurements made with beta ray and scintillation spec-
trometers and coincidence counting techniques.   A theory of the
energy levels of Po-210 has been developed using the method of Pryce
to predict the levels of a nucleus containing two odd protons beyond the
double closed shell from the experimentally known levels of Bi-209,
the nucleus containing a single odd proton beyond the closed shell.
Certain features of the theoretically predicted level scheme and the
experimental level scheme show reasonable agreement.   The spin
assignment for At-210 has been discussed with respect to the log ft
values for its electron capture decay.

((End of Abstract))

((Figure 4 of this article presents an experimental Po-210 level scheme
(energies in kev.))   This scheme is presented as Figure Po-1.

3.5.23   ABSOLUTE ENERGY MEASUREMENT OF ALPHA
          PARTICLES FROM Po-210.   F. A. White, F. M. Rourke,
          J. C. Sheffield, and R. P. Schuman (Knolls Atomic Power
          Laboratory, Schenectady, New York) and J. R. Huizenga
          (Argonne National Laboratory, Lemont, Illinois).
          Physical Review 109, 437-422, January 1958

ABSTRACT

The absolute alpha energy of Po-210 alpha particles was measured by
a 180° magnetic spectrometer.   The value obtained was 5.3054 ±
0.0010 Mev (absolute volts).   Measurement of the energy (α) of the
alpha particles from Cm-214 leading to the ground state of Pu-240 was
made relative to the energy of the Po-210 alpha particles.   A value of
5.8025 ± 0.002 Mev was obtained for this Cm-244 energy.   The energy
difference between the ground state transition α_o and the transition α_l,
to the first excited level of Pu-240 from Cm-24 was found to be 43.5 ±
1 kev.

((End of Abstract))
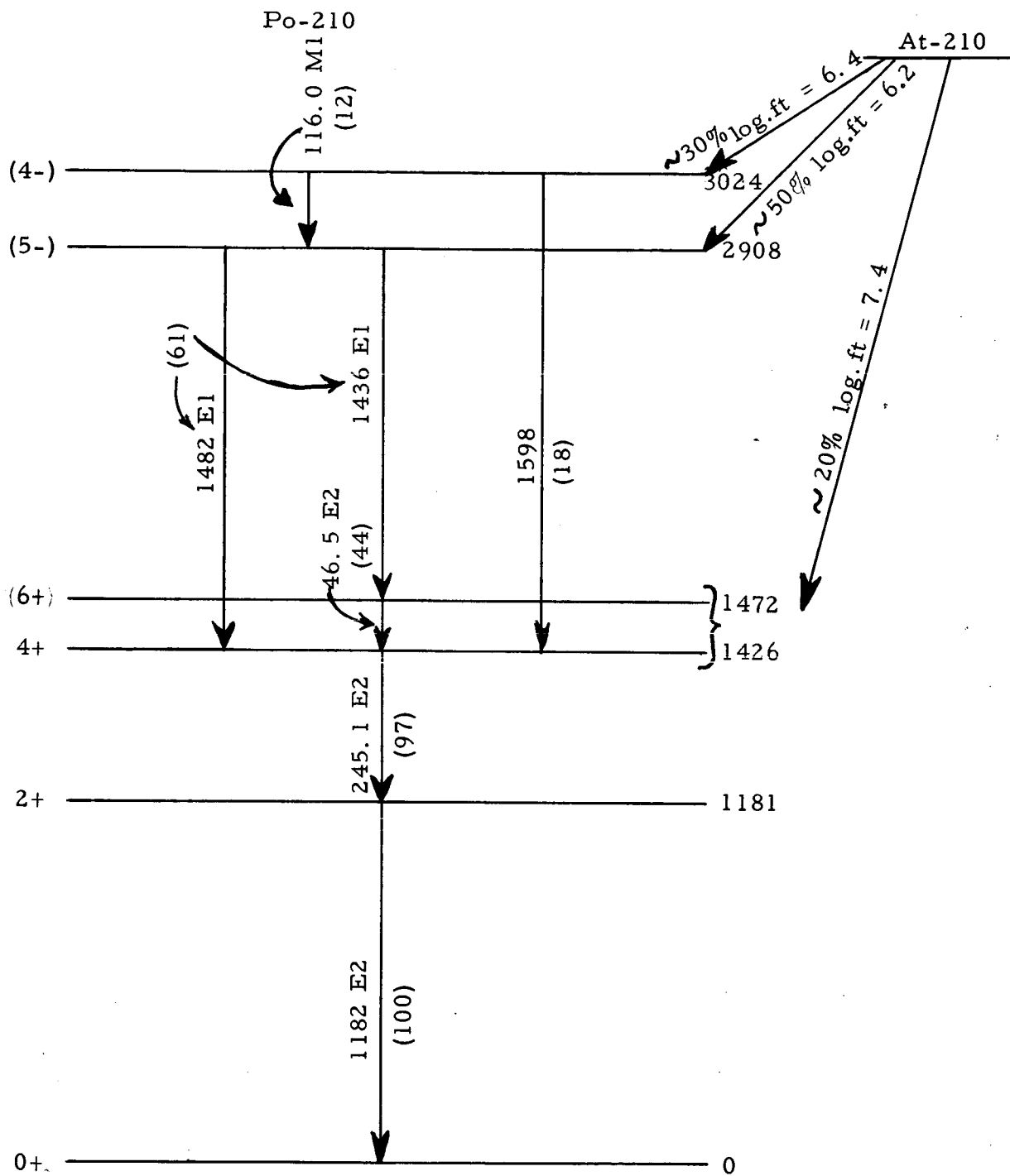
FIGURE Po-1. EXPERIMENTAL Po-210 LEVEL SCHEME

125

The polonium sample was prepared from chemically purified polonium purchased from the Mound Laboratories. No further purification of the polonium was made. The sample used for the energy determination was plated on polished platinum. First a very thin film of copper was electroplated on the platinum; then the polonium was deposited on the platinum from a chloride solution. The final sample showed no discoloration due to either impurities or residual copper.

The curium sample was produced by the very long term irradiation of plutonium in the Materials Testing Reactor. The curium was separated from other actinides and purified from fission products by a series of cation and anion ion exchange column processes. The final curium contained about 98% Cm-244 alpha activity and 2% Cm-242 alpha activity. Just before the source was prepared, plutonium daughter activity was separated from the curium by an anion exchange column process.

The curium sources were made by vacuum-subliming the curium from a tantalum filament through a defining slit onto the polished platinum source holder. The sources showed a slight discoloration of the platinum due either to sublimed tantalum or to solid impurities deposited on the filament with the curium.

3.5.24   ON THE RELATIVE INTENSITY OF Po-210 GAMMA RAYS,
E. E. Ovechkin, Izvestia Akad Nauk SSSR 21, 12, 1641-2
December 1957

ABSTRACT

Experimental evaluation of the relative intensity of the 803 kev gamma rays emitted from the first excited level of Pb-206 in alpha decay of Po-210 is of undoubted interest. In view of the divergence in the data published prior to 1952, we undertook a repeat measurement of the ratio $K_{gamma} = n_{gamma}/n_{alpha}$. The polonium source was prepared by precipitation from a Po-210 nitrate solution after repeated purification to remove all extraneous impurities. The source was sealed in a brass tube 8 millimeters long and 5 millimeters in diameter with a wall thickness of 0.5 millimeters, and had an alpha activity $n_{Po} = 4.10 \pm 0.5$ microcuries according to a calorimetric determination. ((As a result of the work described in this article, the K_γ ratio is set equal to $(1.22 \pm 0.09) \times 10^{-5}$ quanta per decay.))

3. 5. 25   ENERGY OF ALPHA PARTICLES FROM Po-210.   I. I. Agatkin and L. L. Gol'din, Izvestia Akad Nauk SSSR 21, 909-12, July 1957

ABSTRACT

The sources ((used in the experiment described in this article)) were prepared by vacuum evaporation of the radioactive materials Po-210 and Ra-224 from a heated filament onto a glass support.   We suggest ((from the results of the experimentation described in the article)) the value of 5297. 8 $\pm$ 1. 5 kev for the Po-210 alpha particle energy.

3. 5. 26   DETERMINATION OF THE BRANCHING RATIO IN THE DISINTEGRATION SCHEME OF POLONIUM-210.   N. S. Shimanskaia (Radium Institute, Academy of Sciences, USSR).   J. Exptl. Theoret. Phys. (USSR) 31, 174-177, August 1956 (translated in Soviet Physics JETP, Vol. 4, #2, 165, March 1957)

ABSTRACT

Measurements were made of the branching ratio in the disintegration scheme of Po-210.   The probability of transitions to the excited level Pb-206 (with an energy of E = 800 kev) was found to be 1. 2 $\pm$ 0. 2 x 10^{-5}.

The source used by us was a preparation of pure Po-210.   Absence of any noticeable radioactive impurities was confirmed by long time (8 months duration) calorimetric measurements of its disintegration curve as well as of the absorption curve of its gamma radiation in lead.   The decrease of the activity of the source also corresponded to the half life of Po-210 (138. 5 days).   The values of the absolute number of gamma transitions in Po-210 and therefore the values of the branching ratio in the disintegration scheme of this isotope obtained by us were considerably less than those reported in ((3 previous investigations)).   Since the usual ionization or impulse chamber methods were used by these investigators to determine the activity of the polonium source, it was possible that some of the alpha particles were not registered as mentioned above due to the diffusion of the active atoms into the backing material and absorption the surface films. This could result in raising the value obtained for the absolute intensity of nuclear radiation from Po-210.

3.5.27 ON THE RATIO BETWEEN GAMMA AND ALPHA
ACTIVITIES IN Po-210. A. Ascoli, M. Asdente and E.
Germagnoli (Laboratory C.I.S.E. Milano). Nuovo
Cimento 10, 4, 946-7, October 1956

ABSTRACT

Po-210 is known to be a practically pure alpha emitter. Its decay
scheme is given in Figure 1 and its half life is 138.13 days. A direct
measurement of the intensity of emitted alpha particles may be carried
out with satisfactory accuracy if the source is very thin and weak
enough to be introduced into an ionization chamber of well defined
geometry. If the intensity of the source is remarkable its absolute
calibration by means of alpha counting becomes more troublesome and
a current chamber intrinsically capable of less accuracy is generally
used. For the present measurement a thin source whose activity is
approximately four millicuries has been used. It has been supplied
by the Radio Chemical Center of Amersham, England. Po-210 is
electroplated onto platinum and covered with a thin mica sheet (Figure 1
decay scheme of polonium is presented as Figure Po-2).

3.5.28 FINE STRUCTURE AND ANGULAR CORRELATION IN
POLONIUM-210. S. DeBenedetti and G. H. Minton
(Carnegie Institute of Technology, Pittsburgh, Pennsylvania)
Physical Review 85, 944-5, 1955

ABSTRACT

Polonium is usually considered as a pure alpha emitter although the
presence of weak gamma radiation (energy 803 kev, intensity about
10^{-5}/alpha) is definitely established. The low energy alpha particles
preceding these gamma rays have escaped observation despite repeated
attempts to study the fine structure of polonium. By using a coinci-
dence method we were able to detect the low energy alpha group and to
study its angular correlation relative to the gamma rays following it.
The number of coincidences were also studied as a function of
artificial delays introduced in the coincidence selector. The result
indicated that the half life of the gamma emitting state of Pb-206 is
less than 10^{-9} seconds.

3.5.29 THE RELATIVE NUMBER OF GAMMA RAYS FROM
POLONIUM-210. Onofre Rojo, M. A. Hakeem and Max
Goodrich (Louisiana State University). Physical Review
99, 1629, 1955. ((The following is the entire article --
it is not an abstract.))
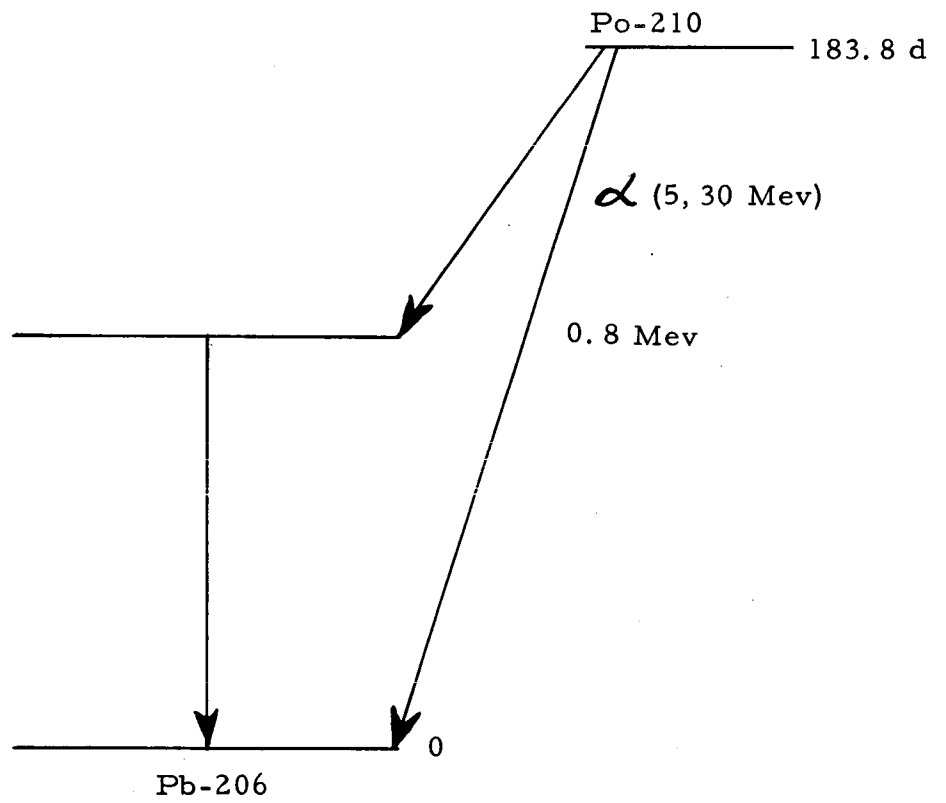
FIGURE Po-2.   DECAY SCHEME OF Po-210

It has long been known that the alpha decay of Po-210 is accompanied by a weak gamma ray of about 800 kev. The number of these gamma rays has been reported to be from 1.5×10^{-5} to 1.8×10^{-5} times the number of alpha rays. In the course of some work on Po-210, the authors have redetermined this ratio using scintillation spectrometer techniques. The alpha ray measurements were made with a plastic scintillator using a diaphragm while the gamma ray measurements were made with a large ((3 inch diameter by 3 inch long)) NaI crystal. The resulting ratio of 1.2×10^{-5} for N_{gamma}/N_{alpha} (estimated error 10%) is believed to be significantly below the published values.

3.5.30   *EXPERIMENTAL STUDY OF INTERNAL IONIZATION IN
             EMISSION.   Michel Riou (Institut du Radium, Paris).
             J. Phys. Radium 16, 583-8 (1955) July (In French)

A review is given of the results on disintegration of Po-210, the most favorable example for the observation of internal ionization. Intensities of K and L rays of lead and of the gamma ray of 800-kev emitted by Po-210 were determined. A deduction of the experimental probabilities of internal ionization of K and L shells, comparison with theory, and results on the electrons emitted by Po-210 are given.

3.5.31   BRANCHING RATIO IN THE DECAY OF POLONIUM-210.
             R. W. Hayward, D. D. Hoppes and W. B. Mann,
             National Bureau of Standards Bulletin 54, 1, 47-50,
             January 1955

ABSTRACT

Using a microcalorimeter to determine the alpha particle activity and a sodium iodide scintillation counter of high efficiency to measure the gamma ray intensity, the branching ratio of Po-210 has been found to be equal to $(1.22 \pm 0.060) \times 10^{-5}$. This value is based on the assumption that the energy of the main alpha particle group from Po-210 is 5.301 Mev. In the calibration of the scintillation counter, the angular anisotropy of the gamma ray from Co-60 were found to be 1.164 ± 0.002.

((Of the two Po-210 sources prepared, the second source was used. It was prepared from some 60 millicuries of solution that had been carefully purified prior to delivery. This purification consisted of depositing Po-210 onto a silver foil from a stock solution containing approximately 130 millicuries of Po-210.)) The silver foil was then

washed free from solution and dissolved in concentrated nitric acid.
After dispelling most of the nitric acid by evaporation, the silver was
precipitated by hydrochloric acid.   The solution was filtered from the
silver chloride and its acidity adjusted for deposition on a second silver
foil which was again processed in the same way as the first.   The
filtrate from the silver chloride being the final solution containing some
68 millicuries of purified Po-210.

3.5.32   *PARTICLES WITH LONG PATH EMITTED FROM
           SOURCES OF POLONIUM.   Marie Ader (College de
           France, Paris).   J. Phys. Radium 15, 60 (1954) January
           (In French)

The origin of particles with long path emitted from Po is uncertain.
It was thought that the particles could be caused by the action of the
alpha rays of Po on the H_2 of the air, the H_2 of the source support, or
the humidity retained in the source support, or the humidity retained
in the source.   However, the 5.2-Mev alpha ray can project in a
hydrogenated substance protons of only 80 u, and paths longer than
300 u, were observed.   The type of source support did not change the
number of long paths.   It was suggested that perhaps a spontaneous
emission of the nuclei of a polonium atom occurred.

3.5.33   CALORIMETRIC DETERMINATION OF THE HALF-LIFE
           OF POLONIUM-210.   J. F. Eichelberger, K. C. Jordan,
           S. R. Orr, and J. R. Parks (Mound Laboratory,
           Monsanto Chemical Company, Miamisburg, Ohio)
           Physical Review 96, 719-721, November 1954

Six determinations have been made of the half-life of polonium with
four different steady-state resistance-bridge calorimeters and five
different samples of polonium.   These six values of the half-life
have been weighed and combined to give a grand-mean value of the
half-life of 138.4005 ± 0.0051 days (internal consistency) or ± 0.0058
day (external consistency).

((End of Abstract))

Five different Po-210 samples were used during a period of three
years.   The polonium was prepared by standard methods but was
sealed in containers fashioned to fit the calorimetric-research needs.
The chemical purity of these samples was not accurately known.
However, the precision of the half-life measurements indicated that

that over the period of the measurements only negligible quantities of radioactive impurities could have been present. Gamma counts and neutron counts of the samples did not indicate the presence of any radioactive impurities in measurable amounts. ((Cited as best value in Rev. Mod. Phys. Vol. 30, No. 2, Pt. II, April 1958.))

3.5.34   *EXPERIMENTAL VERIFICATION OF THE THEORY OF MIGDAL: CASE OF POLONIUM (Po-210). Alphonse Lagasse and Jacqueline Doyen. Compt. rend. 239, 670-2, (1954) Sept. 13. (In French)

Electron and gamma radiations from Po-210 are found to agree with a theory due to Midgal (J. Exp. Theoret. Phys. (USSR) 11, 207 (1941)).

3.5.35   *ON THE THEORY OF MIGDAL. R. R. Roy and M. L. Goes (Univ. Libre de Bruxelles, Belgium). Bull. Classe Sci. Acad. 40, 143-9 (1954) Feb. (In French)

The probability of ionization during the alpha emission of Po-210 was calculated according to the theory of Migdal and compared with experimental results. The general expressions of the energy distribution of electrons are given. A method which allows the separation of the Migdal electrons from the internal conversion electrons is indicated.

3.5.36   *ON THE DECAY OF Po-210. Radha Raman Roy and Marie-Louise Goes. Compt. rend. 237, 1515-17 (1953) Dec. 9. (In French)

Experiments are described for testing a theory due to Migdal concerning the origin of soft 84-kev radiation emitted by the alpha decay of Po-210 to Pb-206. Although accurate agreement was not obtained (within an order of magnitude) between the Migdal prediction and experiment, it is concluded that the observed level is due to the ionization of the atom following alpha decay according to a Migdal process.

3.5.37   (AECD-3536; MLM-575). HALF LIFE DETERMINATION OF POLONIUM-210 BY ALPHA COUNTING. Mary Lou Curtis (Mound Laboratory, Miamisburg, Ohio). ((Also published in Physical Review 92, 1458, December 1953.))

ABSTRACT

A half life of 138.374 ± 0.032 days for Po-210 was determined by alpha counting a sample of approximately 0.5 millicuries over a period of 328 days.

The sample was prepared from a solution of purified Po-210 in nitric acid onto a glass slide.   Mica weighing 0.92 mg/cm^2 was cemented over the sample to prevent migration of activity from the slide.   Tests made by adding air to the evacuated counting chamber and counting the various air pressures showed that the sample was sufficiently thin that no counts were lost by absorption or would be lost by diffusion into the glass.   Over a period of 328 days 81 measurements were made.   Each measurement was of sufficient duration to total at least 500,000 counts to reduce the statistical probable error to 0.1% per measurement.   No geometry factor was used since the decay could be followed from the counting rate.

3.5.38   *X AND GAMMA RADIATION EMITTED BY POLONIUM-
           210.   Michel Riou.   J.Phys.Radium 13, 244 (1952) Apr.
           (In French)

Between 15 and 4000 kev, Po-210 was found to emit only a single gamma ray of 800-kev energy, which is internally converted with emission of Pb K rays with an intensity of 1.6 ± 0.5 x 10^{-6} photons/ alpha particle.   Pb L rays with an intensity of 2.2 ± 0.5 x 10^{-4} photons/alpha were found to arise through alpha particle excitation of Pb present in the source, not through conversion.   The internal-conversion coefficient in the K shell is 10 ± 3%, indicating electric multiple radiation with 2^4 or 2^5 polarity.

3.5.39   FINE STRUCTURE AND ANGULAR CORRELATION IN
           Po-210*. . S. De Bendetti and G. H. Minton (Carnegie
           Institute of Technology, Pittsburgh, Pennsylvania)
           (Received 18 January 1952).   Phys. Rev. 85, 944-5,
           Nov. 1952

Po-210 is usually considered as a pure alpha-emitter, although the presence of a weak gamma radiation (energy 803 kev, intensity about 10^{-5} per alpha) is definitely established.   The low energy particles preceding these gamma rays have escaped observation despite repeated attempts to study the fine structure of polonium.

By using a coincidence method we were able to detect the low energy alpha group and to study its angular correlation relative to the gamma rays following it.

3.5.40   SOME OBSERVATIONS ON THE GAMMA RADIATION FROM POLONIUM.   R. W. Pringle, H. W. Taylor and S. Standil (Physics Department, University of Manitoba, Winnipeg, Canada).   Phys. Rev. 87, 384-5, July 1952

((In this work)) certain observations have been made on the radiations involved ((in the decay of Po-210)) using a coincidence scintillation spectrometer and a weak source of polonium in solution from which all traces of radium and RaD have been removed.   Single channel pulse height distribution analysis gave a value of 804 ± 5 kev for the energy of the hard component.   Several standard gamma ray energies were used for purposes of calibration and the value of 804 kev is a mean for a number of experiments.   No evidence could be found to suggest the presence of any other component in the gamma radiation from polonium in the range 100 kev to 2 Mev.   An estimate has been made of the intensity of the soft component relative to the hard component from a knowledge of the relative counting rates in the apparatus and the detection efficiency of the two radiations.   On the assumption that a soft component is entirely X-radiation following internal conversion of the 804 kev gamma ray, a conversion coefficient is obtained for this radiation of 20 to 30%.

3.5.41   EVIDENCE FOR K SHELL IONIZATION ACCOMPANYING THE ALPHA DECAY OF Po-210.   W. C. Barber and R. H. Helm (Department of Physics, Stanford University, Stanford, California).   Physical Review 86, 275-80, May 1952

ABSTRACT

The radiations of Po-210 have been studied using a NaI scintillation counter in agreement with Grace, Allen, West and Halben.   It is concluded that the soft electromagnetic component probably entirely consists of X-rays of lead.   The region from 25 kev to 2.5 Mev have been examined and with the exception of the known gamma ray of 800 kev, no nuclear gamma rays were observed.   The ratio of the number of K X-rays to the number of 800 kev gamma rays was measured as 0.134 ± 0.025 to 1.   The K shell internal conversion coefficient of the 800 kev transition has been reported as about 0.05

and hence the K X-ray intensity is too great to be explained by internal
conversion alone. The residual gamma rays are attributed to the
process whereby the emission of the alpha particle causes ionization of
the atom. Comparison of the relative intensity of K X-rays and alpha
particles shows qualitative agreement with the probability of this
ionization process as calculated by Migdal.

The polonium was supplied by the Eldorado Mining and Refining
Company who report radioactive impurities of unspecified form of
about 6×10^{-6} milligrams of radium equivalent per millicurie of
polonium. The sources were prepared for use and further purified
by precipitation on nickel foils in 0.1 normal HCl. Later some of the
polonium was purified a second time in the manner described by Lee
and Libby. No spurious lines were observed in the spectra of the
sources either before or after purification. The sources used for
alpha counting were prepared on 0.005 inch foils thick enough to stop
alphas completely so that only one side was effective for alpha counting.

3.5.42   INVESTIGATION OF THE GAMMA RAYS FROM
         POLONIUM.   M. A. Grace, R. A. Allen, D. West, and
         H. Halban (Clarendon Laboratory, Oxford, England).
         Proceedings of the Physical Society (London) 64A, 493-
         507, May 1951

ABSTRACT

A method of standardizing polonium sources by measurement of the
number of gamma rays is described. The hard gamma radiation of
0.773 Mev energy emitted in the decay of Po-210 has been found to
have an intensity of $1.8 \pm 0.14 \times 10^{-5}$ quanta per alpha particle. The
internal conversion of this line to the extent of $6.7 \pm 1.7\%$ gives rise
to K X-radiation of lead. No other soft radiation is detected. The
decay scheme of polonium is discussed.

((End of Abstract))

We were interested in a quantitative determination of the intensity of
hard gamma radiation as a means of providing a simple method of
standardizing polonium. At the same time we investigated the soft
radiation found by Zajac, et al. Whilst our result for the intensity
of the hard radiation is in agreement with the estimate of Zajac, et al,
we have found evidence that the soft radiation is the K radiation of
lead. The following experiments were carried out: (1) measurement

of the source strength by counting alpha particles, (2) measurement of
the intensity of the hard gamma rays, (3) search for gamma rays excited
by alpha particle bombardment of certain elements, (4) critical
absorption measurements on the soft radiation using a scintillation
counter, (5) search for coincidences between soft and hard gamma rays,
(6) critical absorption measurements on the soft gamma rays using a
proportional counter, (7) intensity of electron radiation. The source
was prepared by the electrolytic deposition of about 200 millicuries of
Po-210 from an RaD solution on one side of a platinum foil. This foil
was one centimeter square and about 30 milligrams per square
centimeter thick. The Po-210 had previously been extracted twice by
electrochemical deposition on silver so as to remove as much of the
RaD and RaE as possible. The strength of the RaE content was found
in later measurements to be less than $7 \pm 7 \times 10^{-3}$ microcuries.

((Cited as best value for decay scheme in Rev. Mod. Phys. Vol. 30,
No. 2, pt. II, April 1958.))

3.5.43   NP-1642.   AN INVESTIGATION OF THE ALPHA RAY
            SPECTRUM OF POLONIUM.   John J. Wagner, 1949,
            141 pages.   A dissertation submitted in partial fulfillment
            of the requirements for the degree of Doctor of Philosophy
            in the University of Michigan.

((This document could not be located during the course of the subject
program. Therefore no detailed information can be presented.))

3.5.44   THE PHYSICAL PROPERTIES OF POLONIUM.   III THE
            HALF LIFE OF PONOLIUM.   William H. Beamer and
            William E. Easton (University of California, Los Alamos
            Scientific Laboratory, Los Alamos, Nevada).   Journal of
            Chemical Physics 17, 1298-1300, 1949

ABSTRACT

The half life of polonium has been measured by a calorimetric method.
The reproducibility and precision of the data is much greater than has
been previously reported. The value is found to be $138.3 \pm 0.1\%$ days.

In this investigation two samples were studied. The pure polonium
was electroplated from a dilute nitric acid solution onto a platinum foil.
This foil was placed inside a platinum capsule in a nitrogen atmosphere
and then this was sealed off in a glass ampule after evacuation and
filling with pure helium.

3.5.45   THE ALPHA RAY SPECTRUM OF POLONIUM.   Walter
          G. Wadey (Randall Laboratory, University of Michigan,
          Ann Arbor, Michigan).   Physical Review 74, 1846-53,
          1948

ABSTRACT

Measurements of the alpha ray spectra of polonium mounted on nickel,
silver, and cadmium by means of a 180° focusing magnetic spectro-
graph are reported and discussed.   The weak line series reported by
Chang is not apparent.   The hypothesis is proposed that the alpha ray
spectra seen to date have not been caused by the element polonium but
by the diffusion of the polonium into the mounting metal.

((End of Abstract))

The sources consisted of polonium metal deposited by the Canadian
Radium and Uranium Corporation on one 1-7/16" by 0.020" edge of a
strip of metal 1-7/16" by 0.020" by 1/8".   We were informed that
deposition was made spontaneously by immersion in a polonium
solution relatively free from metallic ions.   The plating time was
approximately 6 hours for a 0.1 millicurie source.   The source
strengths were 0.25 millicurie, 0.1 millicurie, and 0.1 millicurie.

3.5.46   A FURTHER STUDY OF THE GAMMA RADIATION FROM
          POLONIUM.   B. Zajac, E. Broda and N. Feather
          (Department of Natural Philosophy, University of Edinburgh)
          Proceedings of the Physical Society (London) A60, 501-8,
          1948

ABSTRACT

Absorption experiments using lead, gold and tungsten have shown that
in addition to the known gamma radiation of 0.77 Mev energy, polonium
emits other (soft) radiations of which the most intense has a quantum
energy of 84 ± 4 kev.   The intensity of this radiation is of the same
order of magnitude as that of the hard radiation (roughly one quantum
per 10^5 disintegrations).   Experiments by the recoil method indicate
that the emission of the polonium gamma radiation is not delayed by
more than 10^{-1} seconds.   The results of Chang, 1946, concerning the
fine structure of the alpha particles of polonium remained uncorre-
lated with all the other experimental evidence.   Whilst present
information regarding gamma ray energies and intensities may be

reasonably explained, satisfactory explanation of the alpha particle
fine structure "data" appears as remote as ever.

((End of Abstract))

The source was deposited by evaporation of an HCl solution drop by
drop on a polythene disc, 50 mg/cm^2 thick over an area 0.5 centi-
meters in diameter.

3.5.47   THE GAMMA RAYS OF POLONIUM-210.   S. De Benedetti
               and E. H. Kerner (Clinton Laboratories, Oak Ridge,
               Tennessee). Physical Review 71, 122, 1947

ABSTRACT

In connection with Chang's studies on the fine structure of the alpha
particles of polonium and with Tether's discussion on the subject, it
might be useful to report some recent absorption experiments on the
gamma rays of this element. Within the accuracy of the absorption
method ((used in the subject experiment)) it appears that the gamma
radiation of polonium consists of a single component of half thickness
equal to 8.5 grams per square centimeter of polonium. The energy
of the radiation can be evaluated to be 0.8 Mev. The intensity per
curie of polonium is equivalent to that of one of the gamma rays from
7.0×10^{-6} curies of radium when both curves are extrapolated to zero
absorption. A search for softer radiation showed no other components
until with absorbers thinner than 0.5 grams per square centimeter,
aluminum, one finds a radiation whose mass absorption coefficient in
aluminum is 18 square centimeters per gram, and which is probably
the same component observed by Curie and Joliot and attributed by
them to the L line of polonium.

3.5.48   GAMMA RADIATION FROM POLONIUM AND FROM
               LITHIUM BOMBARDED WITH ALPHA PARTICLES.
               Kai Siegbahn (Nobelinstitutet for Fysik) Nature 159,
               471-3, 1947

((The work described in this article shows that)) the gamma radiation
from the polonium is monoenergetic in contradiction to the result
obtained by Bothe. Bothe's value for the energy in the strongest
photo line 0.798 agrees well with ours. If a gamma radiation from
any other energy than 0.773 Mev is emitted from polonium, it is at
any rate extremely weak in comparison with the 0.77s radiation.

3.5.49 A STUDY OF THE ALPHA PARTICLES FROM
POLONIUM WITH A CYCLOTRON-MAGNET ALPHA-RAY
SPECTROGRAPH. W. Y. Chang, Palmer (Physical
Laboratory, Princeton University, Princeton, New Jersey)
Physical Review 69, 60, 1946

PARTIAL ABSTRACT

A description is given of an alpha ray spectrograph consisting of the
Princeton cyclotron-magnet and a plexiglass deflection chamber in
which the alpha particles can be bent into a semicircle of about 80
centimeters maximum diameter. Three different methods of detection
have been employed according to the different strengths of the radio-
active sources. They are the ordinary photographic method, the
counting method and the method of photographic tracks. The behavior
of the spectrograph has been investigated with polonium alpha particles
by the three methods of detection. The forms of the energy distribu-
tion have been determined respectively by these three methods and
agree fairly well with one another. The half width of the main line
under favorable conditions is less than one half millimeter which is
equivalent to about 0.01 Mev. Microscopic examination ((of the
experimental data)) reveals distinctly a series of weak groups in the
low energy region while in the high energy region no indication of any
discreet group has been found.

((End of Abstract))

The behavior of the above spectrograph has been investigated with
polonium alpha particles by using the three methods of detection.
Sources of different forms have been prepared by spinning in RaD
solution thin platinum wire, narrow strips of nickel foils and the
edges (about 0.2 millimeter wide) of nickel foils. All surfaces to be
used for coating with the source have been well polished previously.

3.5.50 BNL-7333. THE PRESENT EXPERIMENTAL AND
THEORETICAL STATUS OF THE PROBLEM OF ELECTRON
EJECTION IN THE ALPHA DECAY OF Po-210. William
Rubinson (Chemistry Department, Brookhaven National
Laboratory, Upton, New York, USA), 11 pages

((This document could not be located either in total or in reference.
Therefore no comments can be made on it.))

3.5.51   MLM-1165 (TR).   POLONIUM.   M. Haissinsky.
         Translated by Robert C. Lange.   AEC Research and
         Development Report (Monsanto Research Corporation)

Table I Polonium isotopes and their nuclear properties (only Po-210 is described here).   Po-210 (RaF: half life, 138.4 days; emissions, alpha; alpha energy, 5.3054 Mev.

THE RADIATIONS.   The alpha rays of Po-210 are essentially mono-energic.   Their energy is 5.3054 Mev which corresponds to a mean range 3.84 centimeters in air at 15° centigrade and 760 millimeter mercury.   The range in water is 39 microns and in nuclear emulsions 21 microns.   Polonium emits approximately 10^5 alpha rays with 5.305 Mev for every particle with 4.5 Mev.   The emissions correspond to the formation of an excited state of radium G.   This energy difference is found as gamma rays of 0.8 Mev and their measured intensity corresponds to 1.25 quanta for every 10^5 alpha particles.   Two other electromagnetic rays of 77 and 10 kev and have weak intensities are also associated with the disintegration of Po-210.   They rise from the perturbation of the electron periphery by the passage of nuclear radiation.   One milligram of Po-210 corresponds to 4.5 curies or approximately 10^{13} disintegrations per minute.   Therefore, the equivalence between 1 curie and 222.2 micrograms of polonium can be calculated.   One curie of Po-210 produces 27.24 $\pm$ 0.11 calories per hour.

3.6   PLUTONIUM-238

HALF LIFE

    (Alpha) 87.48 ± 0.08 years   Ref. 3.6.1 MLM-1196,
    July 10, 1964

    (S.F.) 5.2 x 10^{10} years   Ref. 3.6.8 J. Theoret.
    Phys. USSR 40, 1296-8
    May 1961

NEUTRONS/SPONTANEOUS FISSION

    2.33 ± 0.08   Ref. 3.6.19 Phys. Rev.
    101, 746-50, Jan. 1956

ENERGY LEVELS AND DECAY SCHEME

    Pu-238 $\xrightarrow{\text{ALPHA}}$ U-234

Alpha Energies (Mev)		
5.4912	(72.0%)	
5.4482	(28.0%)	Ref. 3.6.14 Izvestia
5.352	(0.13%)	Akad Nauk 21, 907, 1957
5.208	(5×10^{-3}%)	
5.004	(7×10^{-6}%)	Ref. 3.9.7 Decay Schemes of Radioactive Nuclei Dzhelepov and P. Eker. Pergamon Press 1961

Gamma Energies (kev)		
43.49 ± 0.08		
99.8 ± 0.4		Ref. 3.6.17 Phil. Mag. 1,
153.1 ± 0.6		981-1002, Nov. 1956
203.0		Ref. 3.9.5 Rev. Mod.
810		Phys. Vol. 30, #2, pt. II April 1958

Pu-238

Mev   %

Kev

Uncertain**

0. 0+   810

5. 004 (7×10^{-6})**

8+   499 4

5 208 (5×10^{-3})

5 352   (0 13)

296 4

6+

5. 4482   (28. 0)

5. 4912   (72. 0)

4+   143. 30

2+   43 49

0+   0

U-234
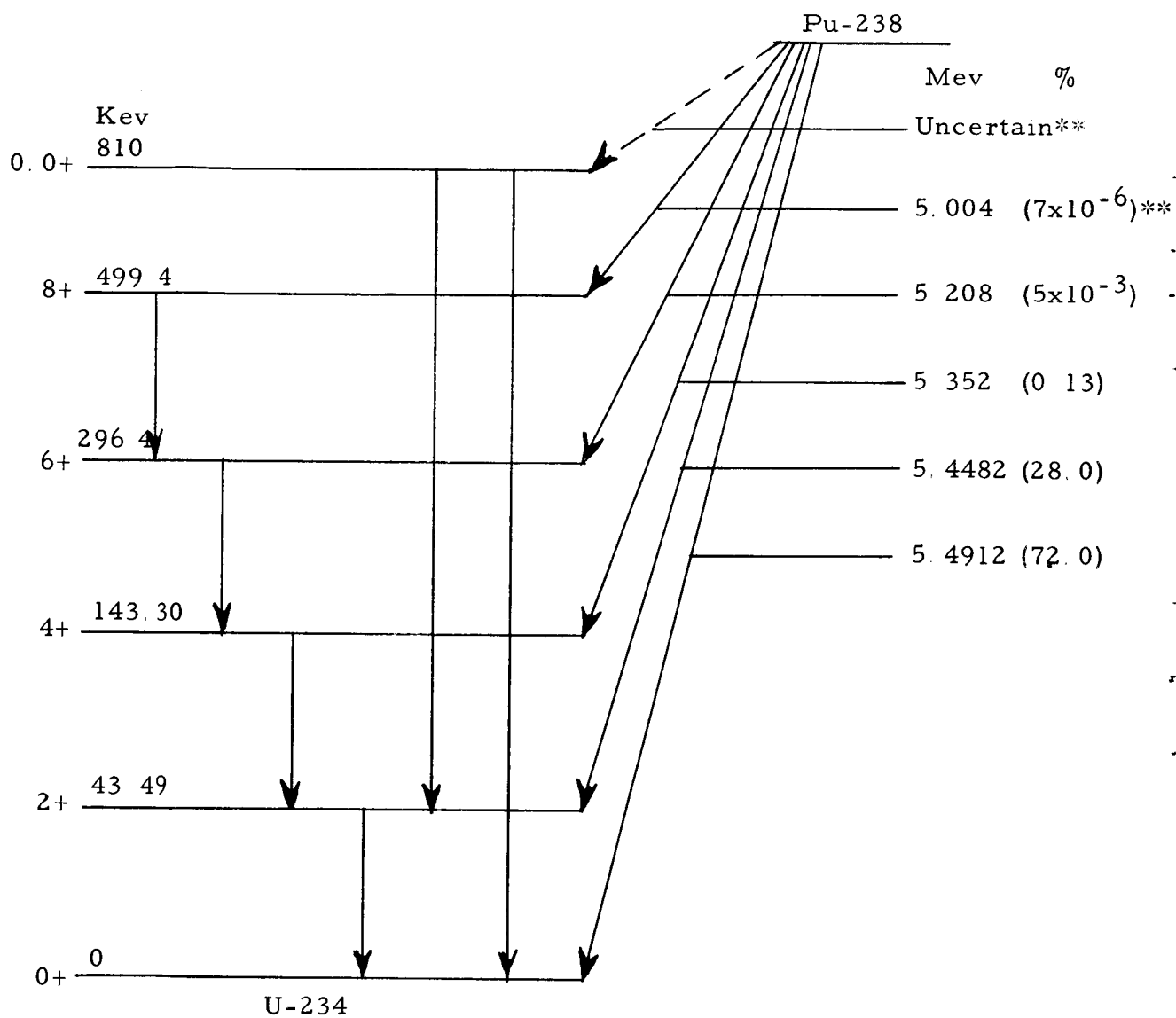
Ref   3 6. 14 also 3. 9. 8

**Ref   3 9 6

Izvestia Akad Nauk SSSR 21, 907, 1957
Reviews of Mod. Phys. Vol. 30 #2 pt II
April 1958.
Decay Schemes of Radioactive Nuclei.
Dzhelepov and P. Eker. Pergamon
Press 1961

3.6.1   MLM-1196.   MOUND LABORATORY PROGRESS REPORT
         FOR APRIL 1964.   J. F. Eichelberger, G. R. Grove,
         and L. V. Jones (Mound Laboratory, Miamisburg, Ohio).
         July 10, 1964.   30 p

PARTIAL ABSTRACT

The half life of Pu-238 was determined by measuring the decay rate of
two samples with Calorimeters 39 and 90.   Each power measurement
was corrected for other isotopes of plutonium, based upon the weight
of the samples and analyses by mass spectrometry.   By propagation
of errors, using the external probable error because it is larger, the
half life and probable error of Pu-238 from this work is 87. 48 ± 0. 08
years**.

**Verified by private communication with Dr. G. R. Grove on 28
October 1964.

3.6.2   LOW-ENERGY GAMMA TRANSITIONS IN Pu-238 AND Pu-
             240.   G. G. Akalaev, N. A. Vartanov, and P. S. Samoilov.
             At. Energ. (USSR), 16: 452-3 (May 1964) (In Russian)

A study was made of the electron and gamma spectra of a mixture of
curium isotopes in a magnetic beta spectrometer with double focusing
and in a scintillation gamma spectrometer.   Spectral line intensity,
electron energy, conversion shell, transition energy, and relative line
intensity are presented for lines in the electron spectrum of Pu-238
and Pu-240, formed in the alpha decay of Cm-242 and Cm-244.   The
ratios of coefficients of internal conversion in E2 transitions with
energies 43 and 44 kev for $Z = 94$ are derived and compared with those
from two other experiments and from theoretical calculations.

3.6.3   ALPHA SOURCES FOR LOW THRUST TASKS IN SPACE.
             W. Diethorn (Nuclear Engineering Department, Pennsylvania
             State University, Pennsylvania).   International Journal of
             Applied Radiation and Isotopes 15, 127-31, March 1964

ABSTRACT

The recoil thrust exerted on a flat plate alpha source is calculated for
alpha particle escape from one side of the source.   The thrust is low
even for the high specific activity alpha emitters Po-210, Pu-238 and
Cm-244 now receiving increased production emphasis.   It is suggested

that these three alpha emitters may find some future applications in space exploration requiring low thrust devices.

((End of Abstract))

((This article presents a theoretical discussion on the maximum thrust capabilities of the subject alpha emitters. Information is also presented in Table 1, not reproduced here, of the chemical and physical properties of the isotopes. The information presented in the table is taken from several other articles.))

3.6.4   TERNARY FISSION OF PLUTONIUM.   N. A. Perfilov, Z. I. Solov'eva, R. A. Filov, and G. I. Khlebnikov, J. Exptl. Theoret. Phys. USSR 44, 1832-6, June 1963. ((Translated in Soviet Physics JETP Vol. 17, No. 6, December 1963.))

ABSTRACT

The energy spectra of long range alpha particles produced in the spontaneous fission of Pu-238 and Pu-240 and in thermal neutron fission of Pu-239 are studied by the nuclear emulsion method. The spectrum shapes are discussed and are compared with the results for complex uranium fission.

((End of Abstract))

In our study of spontaneous fission we used electrolytic films of Pu-238 and Pu-240 containing 78.2 ± 4 and 450 ± 25 micrograms, respectively.

3.6.5   DETERMINATION OF THE ENERGIES OF INTENSE ALPHA GROUPS EMITTED BY THE NUCLEI OF PLUTONIUM-238, 239, 240 AND NUCLEI OF AMERICIUM-241.   Chin-Fan Leang (Centre de Spectrometrie Nucleaire et de Spectrometrie de Masse, Orsay, France).   Compt. Rend. 255: 3155-7 (Dec. 5, 1962) (In French)

The energies of the intense alpha rays of Pu-238, Pu-239, Pu-240, and Am-241 were determined by magnetic spectroscopy with respect to Bi-212 with a precision of 1/7000.

3.6.6   REFER TO 3.7.6.   A SURVEY OF RESEARCH ON THE
         TRANSURANIC ELEMENTS.   Contemporary Physics 2,
         385-402, June 1961

3.6.7   SPONTANEOUS FISSION OF NUCLEI.   K. A. Petrzhak
         and G. N. Flerov, USP. Fiz. Nauk. 73, 655-683, April
         1961.   ((Translated in Soviet Physics USPEKHI, Vol. 4,
         No. 2, September-October 1961.))

((The subject article is more or less a primer on the subject of
spontaneous fission of nuclei.   It contains no specific experimental
information but is of value as far as basic understanding of spontaneous
fission is concerned.   It contains a history of the study of spontaneous
fission from the 1930s up through the date of the article.))

3.6.8   SPONTANEOUS FISSION PERIODS OF Np-237, Pu-238
         and Pu-242.   V. A. Druin, V. P. Perelygin and G. I.
         Khlebnikov (Joint Institute for Nuclear Research).   J.
         Exptl. Theoret. Phys. (USSR) 40, 1296-8, May 1961,
         translated in Soviet Physics JETP Vol. 13, No. 5,
         November 1961

ABSTRACT

An attempt has been made to determine the true spontaneous fission
half period of Np-237 by employing nuclear photographic emulsions
prior to development.   The photographic plates were treated with
potassium ferrocyanide to remove the background alpha particle
tracks.   The reliability of this method was checked by measuring the
spontaneous fission half periods of Pu-238 and Pu-242 which were
independently determined using a proportional counter.   The results
obtained for plutonium by the various methods are identical and agree
with other available data.   Only three fragment tracks were detected
in the Np-237 photographic measurements.   Thus only a lower limit
of 10^{18} years can be established for the half period as compared with
the usually accepted value of 4×10^{16} years.

((End of Abstract))

Seven samples were prepared, three of Np-237, two of Pu-238 (0.27
and 0.35 micrograms) and two consisting of a mixture of the isotopes
Pu-238 (14%) and Pu-242 (86%) and containing 0.37 and 0.80 micro-
grams of Pu-238, respectively.   As a result of the measurements,

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the following values for the half periods were obtained: 5.2×10^{10} years for Pu-238 and 6.7×10^{10} years for Pu-242.

3.6.9   THE DECAY OF NEPTUNIUM-238.   R. G. Albridge and
J. M. Hollander (Lawrence Radiation Laboratory and
Department of Chemistry, University of California,
Berkeley, California).   Nuclear Physics 21, 438-449, 1960

ABSTRACT

A study has been made of the energy levels of Pu-238 which are postulated by Np-238 beta decay or by examination of the Np-238 conversion electron spectrum in high resolution beta spectrographs. The general features of the level scheme as previously given are unchanged but several new transitions are observed with energies of 119.8, 871, 943, 989, and 1034 kev and two new levels are postulated at 915 and 1034 kev which accommodate all but the 943 kev transition. A possible assignment of the 943 kev transition to the (0 +, 0) state of the beta vibrational band is discussed.   In addition the weak 885 kev transition from the 2+ state of the gamma vibrational band to the 4+ state of the ground band is seen and its relative intensity determined. Comparisons are made of the experimental relative intensities of the three photons depopulating this band with those predicted from the rules of Alagla, et al.   Only fair agreement is noted.   A discussion is given of the beta decay branchings and log ft values of Np-238 decay in terms of the postulated characters of the Pu-238 states and the measured standard of Np-238.

((End of Abstract))

An Np-238 sample was prepared by a five hour neutron irradiation of approximately 200 micrograms of Np-237 in the materials testing reactor at Arco, Idaho.   The sample was dissolved in concentrated HCl and the neptunium precipitated with $Zr_3(PO4)_4$ after reduction to the +4 state by ++.   Further purification was effected by cold precipitation with LaF_3 and $La(OH)_3$ to separate the neptunium from lanthanum and other rare earths.   The solution was passed through a Dowex A-1 anion column at high fluoride concentration and the neptunium subsequently elutriated with one molar HCl.   This sample was electroplated onto a 0.25 mm platinum wire which served as a source for the spectrographs.   ((The subject article is concerned primarily with the decay scheme of Np-238 ending in the Pu-238 level. It may be of interest to those wishing to have a complete picture of the decay scheme of Pu-238 to reference this article.))

3.6.10   ENERGY LEVELS OF Pu-238 AND Pu-239 NUCLEI.
           S. A. Baranov and K. N. Shlyagin.   p. 393-407 of
           "Soviet Research on the Lanthanide and Actinide Elements,
           1949-1957.   PART III.   Nuclear Chemistry and Nuclear
           Properties." (In English Translation.)   New York,
           Consultants Bureau, Inc. (1959)

ABSTRACT

The beta and gamma transitions in the decay of Np-238, Np-239, and
Cm-242 were investigated using beta spectrometer, scintillation
spectrometer, and proportional counter techniques.   Possible spin
values of the Pu-239 nuclear levels were determined and a hypothesis
established as to the possibility of the existence of rotational levels
for this even-odd nucleus.   Possible energy level schemes for Pu-
283 and Pu-239 are presented.

3.6.11   SPECTRUM OF THE INTERNAL CONVERSION ELECTRONS
           ACCOMPANYING DECAY OF Pu-238 AND Pu-240.   E. F.
           Tretyakov, L. N. Kondrat'ev, G. I. Khlebnikov and L. L.
           Gol'din, J. Exptl. Theoret. Phys. USSR 36, 362-366,
           February 1959.   ((Translated in Soviet Physics JETP
           Vol. 36, No. 2, August 1959.))

ABSTRACT

The spectrum of conversion electrons accompanying the alpha decay
of Pu-238 and Pu-240 was studied by means of a high transmission
magnetic spectrometer with toroidal field shape which measured
alpha-electron coincidences.   Transitions from the 6+ excited levels
were detected and the multi-polarity and more precise energy values
were determined for transitions from the 4+ and 2+ levels.

3.6.12   NUCLEAR SPECTROSCOPY.   I. Perlman (Lawrence
           Radiation Laboratory, University of California, Berkeley).
           Proceedings of the National Academy of Science, U.S.,
           45, 461-70, April 1959

((This paper deals with nuclear states in the heavy element region and
how information is obtained from the study of alpha radioactive
substances.   The article is entirely theoretical in nature and is in the
form of a basic study of nuclear spectroscopy.   It contains no
particular experimental information.))

3.6.13   ELECTRIC MONOPOLE TRANSITIONS IN Pu-238 AND U-234. I. Perlman, Frank Asaro, E. G. Harvey and F. S. Stephens, Jr. (University of California, Berkeley). Bul. of the American Physical Society, Series II, Vol. 2, 394 December 1957.

((The following is the entire reference presented in this document.))

Electric monopole transitions in Pu-238 and U-234 were seen following the alpha decay of Cm-242 and Pu-238, respectively. An anthracene crystal spectrometer was necessary to register the weak K and L + M lines which occurred in fewer than 1×10^6 alpha disinte-grations. The K/L + M ratios were 4.5 which agrees with the value 5 given by theory for an EO transition. Each EO transition was shown to lead to an excited 0+ state to the 0+ ground state and to compete with an E-2 gamma ray from the same excited level to the 2+ state of the ground state rotational band. This competition will be discussed in terms of the theory. The EO assignment was made by determining minimum values for the conversion coefficients and showing that the high values so obtained could not arise from high multi-polarity (M4 or above) transitions. The excited 0+ state in Pu-238 is at 935 kev and that for U-234 at 810 kev. The U-234 state is undoubtedly the same as that previously seen following the beta decay of UX_2.

3.6.14   ALPHA DECAY OF PLUTONIUM-238. L. N. Kondrat'ev, G. I. Novikova, V. B. Dedov, and L. L. Gol'din, Izvestia Akad Nauk USSR, 21, 907-8, July 1957

Knowing the alpha decay intensities to successive levels of one rotational band, we can draw certain conclusions regarding the shape of the daughter nucleus. In view of this, accumulation of experimental material on alpha decays is of considerable interest. In the present work we investigated the highest excited rotational states of U-234 evidenced in alpha decay of Pu-238. The Pu-238 was obtained as a product of alpha decay of Cm-242 formed by slow neutron bombard-ment of Am-241. The elements were separated by chromatographic method. The separation of the plutonium from the americium was so thorough that no trace of Am-241 alpha lines appeared in the recorded spectra. ((As a result of the subject investigation alpha decay schemes for Pu-238, and energy levels of U-234 are presented as Figure 2, and is shown as Figure Pu-1.))

8+   499 kev 7×10^{-6} %

288 kev

6+

141.5 kev

4+

43.7 kev

2+

0+   U-234

Pu-238

α

5.208 Mev 5×10^{-3} %

5.3521 Mev 0.13%

5.4482 Mev 28.8%

5.4912 Mev 11.1%
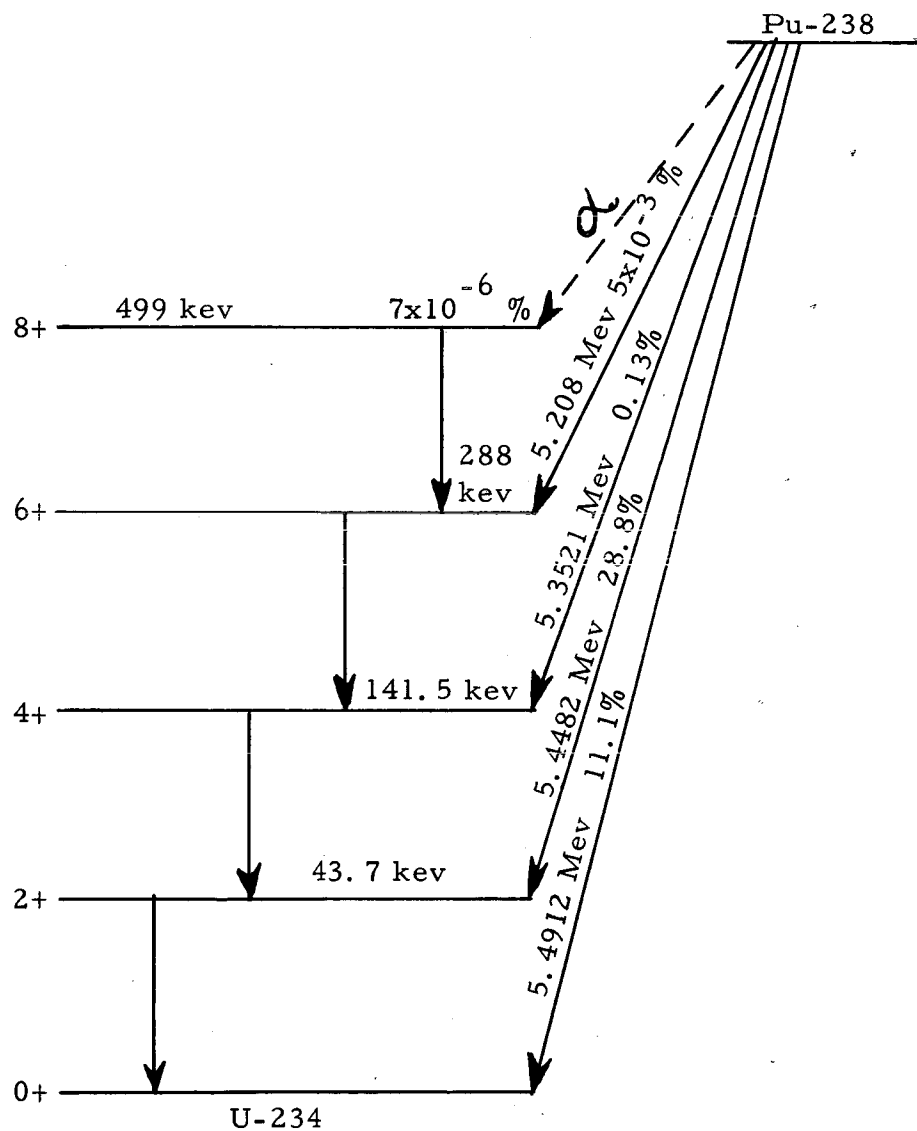
FIGURE Pu-1.   ALPHA DECAY SCHEME FOR Pu-238 AND
ENERGY LEVELS OF U-234

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3.6.15　　HALF LIFE OF Pu-238.　Darleane C. Hoffman, George P. Ford and Francine O. Lawrence (University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico).　Journal of Inorganic and Nuclear Chemistry 5, 6-11, 1957

ABSTRACT

The half life of Pu-238 has been measured by determining its rate of growth from Cm-242.　The weighted average of two determinations is 86.41 years with an estimated error of 0.3 years.

((End of Abstract))

The Cm-242 used in the experiment was produced by thermal neutron irradiation of Am-241 and initial hot lactate cation resin column was used to separate the bulk of the Am from the Cm.　The alpha activity from Cm-243 and Cm-244 corrected to 12 July 1955, the time of standardization of the curium solutions, was calculated to be 0.88% of the Cm-242 alpha activity.　((A substantial portion of this article is devoted to the preparation and analysis of the purities of samples and is too extensive to be covered in this annotated bibliography.))

3.6.16　　ENERGY LEVELS OF Pu-238 and Pu-239 NUCLEI.　S. A. Baranov and K. N. Shlyagin.　Soviet J. Atomic Energy, No. 1, 51-65 (1956)

ABSTRACT

A double-focusing magnetic beta spectrometer, a gamma scintillation spectrometer, and a proportional counter were used to study the radiations from Np-238, Np-239, and Cm-242.　Resultant spectra are shown, and the level schemes of the Pu-238 and Pu-239 nuclei are given.

3.6.17　　GAMMA RADIATION FROM THE DECAY OF PLUTONIUM-238, CURIUM-242, CURIUM-243.　J. O. Neuton, D. Rose and J. Milsted (Atomic Energy Research Establishment, Harwell).　Philosophical Magazine 1981-1002, November 1956

ABSTRACT

Accurate measurements on the gamma rays from the decay of Pu-238 and Cm-242 have been made with proportional counters. Values of 43.49 $\pm$ 0.08 and 99.8 $\pm$ 0.4 and 153.1 $\pm$ 0.6 kev for Pu-238 and 44.03 $\pm$ 0.06, 101.80 $\pm$ 0.17 and 157.61 $\pm$ 0.3 kev for Cm-242 were obtained. The ratios of these energies for each nuclide agree well with those predicted in the strong coupling limit of the unified model. Gamma rays having energies of 210 $\pm$ 1.5, 228 $\pm$ 2, and 277 $\pm$ 2 kev and K-X radiation were found from the decay of Cm-243. These gamma rays are shown to be magnetic dipole with a 30% mixture of electric quadrupole. The magnetic dipole component is 10^4 times slower than the single particle estimate.

((End of Abstract))

Preparation of Cm-242 and Pu-238 sources: two samples of curium were used in the present work, one from an irradiation in BEPO at Harwell and the other from a much more intense irradiation in the NRX reactor at Chalk River. The integrated neutron doses for these irradiations were approximately 2 x 10^{18} and 10^{20} n/cm^2, respectively. It is unlikely that an appreciable amount of Cm-243 was formed in the BEPO irradiation but a fractional percentage by weight of this isotope could have been formed in the NRX irradiation by further neutron capture in Cm-242. In each case the curium was separated from the irradiated americium by the following chemical steps - precipitation as a fluoride from a solution in which the americium has been oxidized to the fluoride soluble hexavelant state, separation from rare earth by elutriation from cation exchange column with 12 normal hydrochloric acid, separation of curium from residual americium by elutriation from a cation exchange column with ammonium citrate solution at 85° centigrade.

Pu-238, the alpha daughter of 162 day curium-242, was extracted from purified curium fractions which had been standing several months by a further ion exchange step. The plutonium fraction was purified chemically by conventional solvent extraction and precipitation reactions on an ultra micro scale. The Pu-238 used in the present work was shown by pulse analysis to contain negligible amounts of Cm-242 and other alpha emitters. ((The decay schemes for Pu-238 and Cm-242 are presented as Figure 9 in this article. The decay scheme for Pu-238 is presented as Figure Pu-2. The decay scheme for Cm-242 is presented in Section 3.7.))
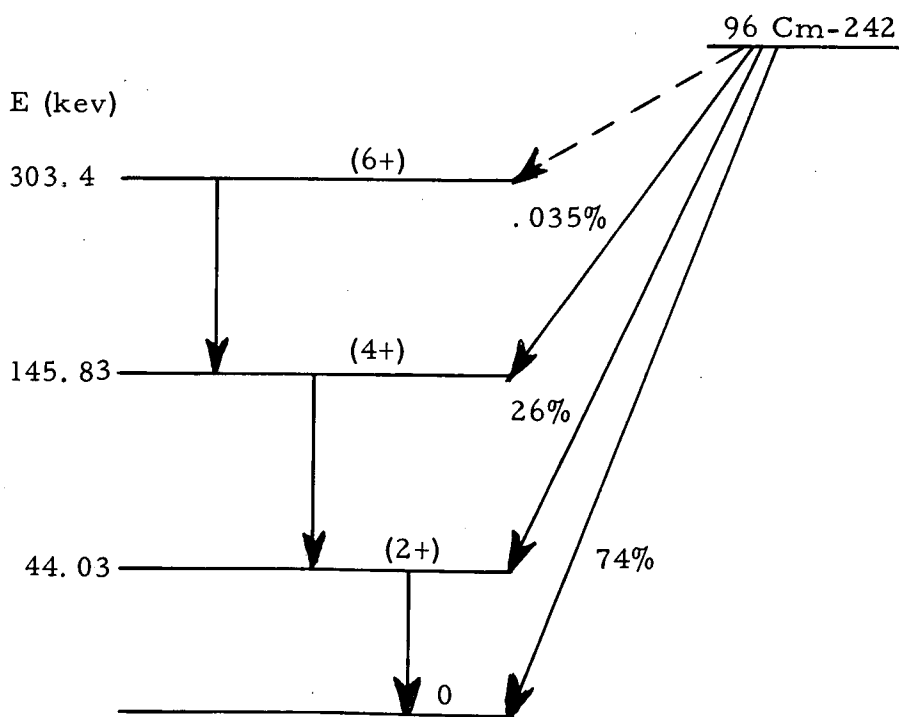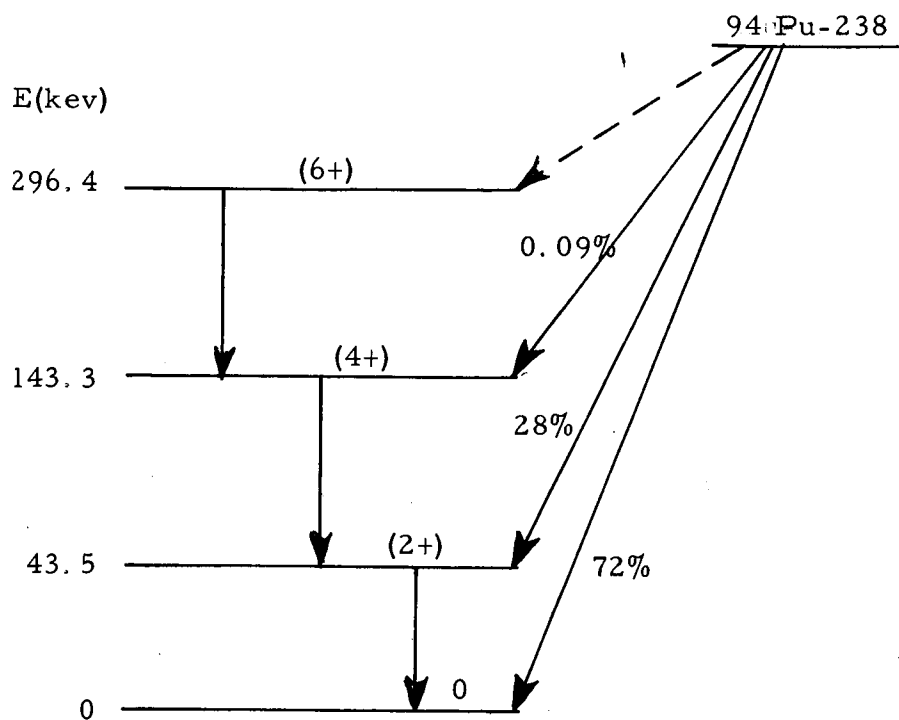
FIGURE Pu-2.   DECAY SCHEMES FOR Pu-238 AND Cm-242

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3.6.18   FIRST EXCITED STATES OF HEAVY EVEN-EVEN
          NUCLEI.   Jack M. Hollander (Radiation Laboratory and
          Department of Chemistry, University of California,
          Berkeley, California).   Physical Review 103, 1590-1,
          September 1956

The systematic behavior of first excited states of even-even nuclei is
well known, and indeed the pronounced maxima of the first excited
state energies at the "magic numbers" are among the most striking
manifestations of nuclear shell structure.   Between the closed shells,
in the regions $155 < A < 185$ and $A > 225$, rather flat minima are
developed whose constancy and low energy point to the collective
nature of the excitations.   It is the purpose of this letter to assemble
some recent data which illustrates the "second-order" systematics of
these excited states.   Most of the energies quoted here were obtained
from precision measurements of conversion electron spectra in the
Berkeley permanent-magnet beta spectrographs.   These data are
given in Table I.   ((The information contained in Table I as it pertains
to this bibliography is presented as follows:))

	Isotope	Energy (kev)	Lines Seen	Measured from
	Pu-238	44.11 ± 0.05	L_{II}, L_{III}, M_{II}, M_{III}, N_{III}, O	Cm-242
1.	Cm-242	42.12 ± 0.06	"	Am-242m
2.	Cm-242	42.18 ± 0.1	"	Am-242m

3.6.19   PROBABILITIES OF PROMPT NEUTRON EMISSION FROM
          SPONTANEOUS FISSION.   Donald A. Hicks, John Ise, Jr.,
          and Robert V. Pyle (Radiation Laboratory, University of
          California, Berkeley, California).   Physical Review 101,
          1016-1020, Jan. 1956

ABSTRACT

The neutron number distributions from the spontaneous fission of
seven isotopes have been measured by the use of a cadmium plated
liquid scintillation tank.   The experimental distributions can be

roughly approximated by binomial distributions. The average number of neutrons per spontaneous fission have been found to be 2.30 ± 0.19 for Pu-236, 2.33 ± 0.08 for Pu-238, 2.257 ± 0.046 for Pu-240, 2.18 ± 0.09 for Pu-242, 2..65 ± 0.09 for Cm-242 and 2.84 ± 0.09 for Cm-244.

((End of Abstract))

The nuclide to be investigated was mounted as a very thin sample upon a platinum foil which served as the cathode in a 3" diameter parallel plate fission chamber.

3.6.20   ALPHA-SPECTRA OF HEAVY ELEMENTS.   L. L. Gol'din, E. F. Tret'yakov, and G. I. Novikova.   p. 226-50 in Meetings of the Division of Physical-Mathematical Sciences.   Session of the Academy of Sciences of the USSR on the Peaceful Use of Atomic Energy.   July 1-5, 1955.   Moscow, Publishing House of the Academy of Sciences of the USSR, 1955.   376 p. (In Russian)

PARTIAL ABSTRACT

The alpha particle spectra were studied, utilizing a 50 cm radius precision double-focusing magnetic alpha spectrometer with 2×10^{-4} of 4 pi transmission and 7.5 kev resolution, determined as half-maximum width. The automatic stabilization of coil current secured 0.01% long-time stability. The spectrometer construction was preceded by an extensive study of the theory of particle focusing in magnetic fields with cylindrical symmetry. The spectra of U-233, U-234, Pu-238, Pu-239, Pu-240, Am-241 and Pa-231 were studied. The alpha spectrum of Pu-238 contains 2 groups: 5490.9 kev (60%) and 5449.9 kev (31%).

3.6.21   BETA EMITTER Np-238, II SCINTILLATION SPECTROS-COPY IN COINCIDENCE STUDIES.   John O. Rasmussen, Frank S. Stephens, Jr., Donald Strominger (Department of Chemistry and Radiation Laboratory, University of California, Berkeley, California).   Physical Review 99, 47-55, July 1955

ABSTRACT

The relative intensities of electromagnetic radiation from Np-238, determined by scintillation spectroscopy set an upper limit for K

capture of K/beta as less than 1%. On the basis of extensive
scintillation counter coincidence measurements together with the beta
spectroscopic results of the preceding article two alternate decay
schemes differing only in minor detail are proposed for Np-238. The
levels of Pu-238 involved are three close line ground rotational band
members and a cluster of three levels near 1.0 Mev. Two of which
appear to belong to the same rotational band. Conversion coefficient
determinations permit multi-polarity assignments for a number of the
gamma transitions and consequent spin and parity assignments for a
number of excited states. Selection rules and other intensity rules
involving the Bohr-Mottelson K quantum numbers are tested providing
K assignments for levels. There is a high degree of K purity of
these states where tests were possible. The question of possible
"vibrational" character of the band near 1 Mev is discussed specula-
tively.

((End of Abstract))

((Figure 3 and Figure 4 presented as a part of this article give
possible decay schemes for Np-238 which, in part, include partial
decay schemes for Pu-238. Because these decay schemes do not
deal directly with Pu-238, they are not reproduced here. It may be
of some interest to refer to the original article for examination of
these figures.))

3.6.22   ANL-5420. DECAY SCHEMES OF THE TRANSURANIC
          ELEMENTS. Eugene L. Church. Argonne National
          Laboratory, Physics Division, Summary Report, August
          1954 - February 1955. Page 35, Section 37.6.

Plutonium-238 is a 90 year even-even alpha emitter decaying to U-234.
The conversion electrons spectrum of this activity has been previously
examined and transitions of 43.6 ± 0.3 and 100.0 ± 0.4 kev recorded
in uranium. These transitions are below the threshold for K conversion
and convert only to the L, M and higher shells. In the present
experiments conversion lines corresponding to the various L and M
subshells were resolved and both transitions found to convert almost
entirely to the II and III subshells.

3.6.23   NUCLEAR PROPERTIES OF THE PLUTONIUM ISOTOPES.
          G. T. Seaborg book, The Actinide Elements, McGraw-
          Hill Book Company, Inc., 1954

((Chapter 7, under table 7.1, radioactive properties of plutonium isotopes, the following information is given for Pu-238.)) Half life, 89.59 ± 0.37 years; mode of disintegration radiation and energies, alpha 5.495 (76%) 5.453 (24%) 5.351 (0.15%), gamma 0.044, 0.101, 0.149 and conversion electrons; modes of formation: Np-238 beta-decay, U-238 (alpha, 4n), U-235 (alpha, n), Np-237 (d, n), Cm-242 alpha decay.

Seaborg, James and Ghiorso found that the alpha emitting isotope Cm-242 was produced from the Pu-239 (alpha, n) Cm-242 reaction, first using 32 Mev helium ions in this bombardment. Soon after the former method of production was discovered, these investigators found that the same isotope could be produced as a result of high order neutron reactions during the neutron irradiation of Pu-239. ((The balance of this article presents a short history on the half life determinations, the spontaneous fission rate, etc., of Cm-242.))

Curium-244, Reynolds, Hulet, and Street have identified Cm-244 in a mass spectrographic examination of the curium fraction from a highly neutron irradiated americium sample. ((Article goes on to present a short history of the determination of the various properties of Cm-244.))

3.6.24   CORRELATION OF SPONTANEOUS FISSION HALF LIVES. M. H. Studier and J. R. Huizenga (Argonne National Laboratory, Lemont, Illinois). Physical Review 96, 545-6, October 1954

ABSTRACT

Empirical correlations which can be used in predicting the properties of undiscovered elements and isotopes are of great practical value. Many such relationships involving alpha disintegration and spontaneous fission rates have been published. Recently alpha disintegration and spontaneous fission half lives of a number of newly discovered nuclides have been measured. We have observed that linear lines connecting even-even nuclides differing by two Z units and six A units give better extrapolated values of R than linear lines connecting the alpha decay products. In general alpha disintegration half lives of even-even isotopes of a given element beyond the double closed shell decrease with increasing Z^2/A values, whereas the spontaneous fission half lives of even-even isotopes go through a maximum with increasing Z^2/A values. However, it is interesting to note that R values increase with increasing Z^2/A values for the even-even isotopes for the given

element (Table 1 entitled "Alpha Disintegration in Spontaneous Fission Half Lives" give references for these properties of 29 isotopes. Included in these are the alpha disintegration and spontaneous fission half lives for Pu-238, Cm-242 and Cm-244. These are reproduced as follows: Pu-238, alpha half life in years 90, fission half life in years 4.9×10^{10}, fission half life in years/alpha half life in years 5.4×10^8; Cm-242 alpha half life in years 0.445, fission half life in years 7.2×10^6, fission half life in years/alpha half life in years 1.6×10^7; Cm-244 alpha half life in years 18.4, fission half life in years 1.4×10^7, fission half life in years/alpha half life in years 7.6×10^5).

Chapter 20, Slow Neutron and Spontaneous Fission Properties of Heavy Nuclei, by J. R. Huizenga, W. M. Manning, and G. T. Seaborg ((this article is concerned with a description of the spontaneous fission of the various transuranic elements)). The following information is given for Pu-238, Cm-242, and Cm-244. Nuclide Pu-238 fissions per gram hour, 36, half life in years 5.5×10^{15}; Cm-242 fissions per gram hour 3×10^{10}, half life in years 6.5×10^6; Cm-244, fissions per gram hour $(1.4 \pm 0.2) \times 10^{10}$, half life in years 1.4×10^7.

3.6.25   THE ALPHA- AND GAMMA-RAY SPECTRA OF Pu-238. Frank Asaro and I. Perlman (Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California). Physical Review 94, 381-4, April 1954. ((Also published as UCRL-2419.))

ABSTRACT

The alpha and gamma spectra of Pu-238 have been studied with an alpha-particle spectrograph and gamma-ray scintillation and proportional counters. Alpha groups of 5.495 (72 per cent), 5.452 (28 per cent), and 5.352 Mev (0.09 per cent) and electromagnetic radiations of 17 (13 per cent), 43.8 ± 0.5 (0.038 per cent), 99 ± 2 (0.008 per cent), and 150 ± 2 kev (0.001 per cent) were observed. Spins and parities are assigned to the energy levels, and the results are evaluated with respect to the developing theory and systematics of complex alpha spectra and excited states of even-even nuclei.

((End of Abstract))

The samples of Pu-238 used in the measurement were made by prolonged neutron irradiation of Am-241. The primary objective of

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the irradiation was to make Pu-242 through the electron capture branching of 16 hour Am-242m so sizable amounts of this isotope were present. ((Three samples in all were prepared.))

All samples were mounted by vacuum sublimation of plutonium chloride onto a platinum plate which was masked to present a band 1 in x 1/8 in.   The alpha particles were caught on a photographic plate and the track count plotted according to position on the plate in order to reproduce the spectrum.

Gamma-ray spectra were measured for the most part with a sodium iodide scintillation counter coupled with either a single channel or multichannel pulse-height analyzer.   In some experiments a xenon-filled proportional counter was used to produce the pulse for the analyzer.

((Subjects discussed in detail in this article include the principal alpha groups of Pu-238, the low intensity alpha groups of Pu-238, the gamma rays of Pu-238, the 43.8 kev gamma ray, the L X-rays, the 99 kev gamma rays and the 150 kev gamma rays.))

((Also presented in this article are decay schemes for Cm-242 and Pu-238.   These decay schemes are shown in Figure Pu-3.)) ((Cited as best value for decay scheme in Rev. Mod. Phys. Vol. 30, #2, pt II, April 1958.))

3.6.26   THE RADIATIONS OF Np-238 AND THE HALF LIFE OF
           Pu-238.   Paper 14.2 by A. H. Jaffey and L. B.
           Magnusson, 1003-5, National Nuclear Energy Series,
           Division IV, Plutonium Project Record, Vol. 14B, pt II,
           1951, paper 6.40 to 22.80.

((The half life of Pu-238 as determined by these authors equals 77 years.   Authors point out the fact that the half life of Pu-238 had been previously determined as 89 ± 9 years and 92 ± 2 years.   These experiments indicate that the Pu-238 half life is probably close to 90 years.   If either of these values is correct, then the experimental value ((as determined by these authors)) must be too small.))

3.6.27   AECD-3149.   SPONTANEOUS FISSION.   Emilio Segre.
           Los Alamos Scientific Laboratory, May 8, 1951.   Page
           30.   ((Also published in Physical Review 86, 21-28, 1952))
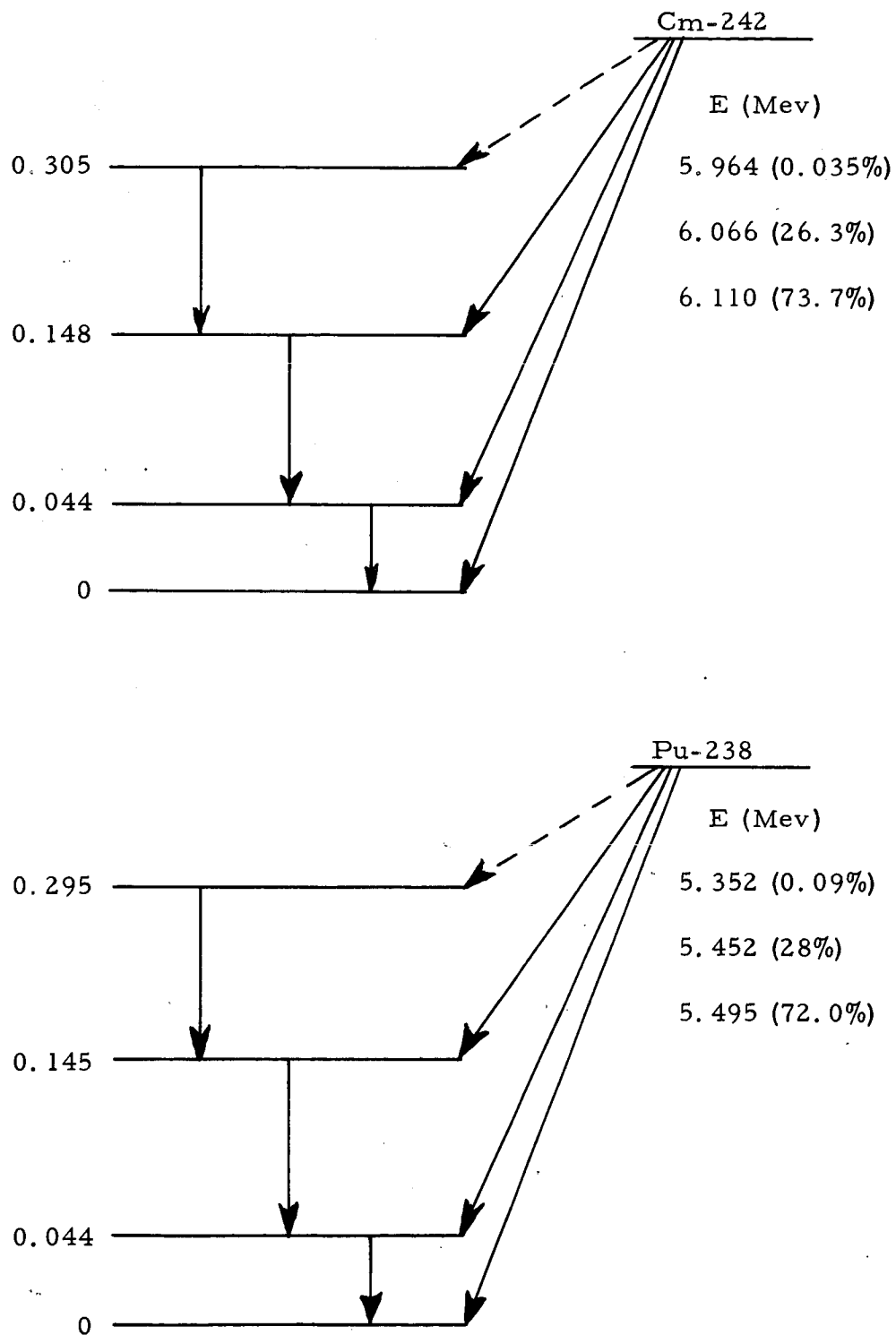
FIGURE Pu-3.   COMPARISON OF ALPHA SPECTRA OF
Cm-242 AND Pu-238

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This substance was prepared by a (d, 2n) reaction on U-238 and it has a half life of about 60 years. The Pu-238 was evaporated on platinum discs and the effective amount present was measured by observing the slow neutron fission of the contaminated Pu-239 and using the ratio of the alpha activities quoted above. In each of our three samples, we had approximately 10^{-5} grams of Pu-239 and 2×10^{-8} grams of Pu-238 effective. The samples were observed for 830 hours total corresponding to 18.8×10^{-6} gram hours for Pu-238 and 8.6×10^{-3} gram hours for Pu-239. 144 fissions were counted. From this we deduce a spontaneous fission decay constant of 2.1×10^3 fissions per gram per second. The possible contribution of other plutonium isotopes to spontaneous fission is negligible, being at the most on the order of 1% of the total observed.

((Note: the half life mentioned above, 60 years, is incorrect and was probably the reference cited in ANL-4286.))

3.6.28   ENERGY LEVELS OF Pu-238 AND Pu-239 NUCLEI.
          S. A. Baranov, K. N. Shlyagin, Atomic Energy USSR 2,
          50, 1950.

((In this article the decay schemes of Cm-242 and Pu-238 are discussed. This article is in Russian, however, and no attempt at translation has been made.))

3.6.29   HALF LIFE FOR DOUBLE BETA DECAY.   C. A. Levine,
          A. Ghiorso and G. T. Seaborg (Department of Chemistry
          and Radiation Laboratory, University of California,
          Berkeley, California).   Physical Review 77, 296, 1950.
          (Also published as AECD-2741)

((The subject experiment)) consists of examining uranium samples for 90 year Pu-238 which would come from U-238 by the double beta particle mechanisms since Np-238 is heavier than U-238, which, in turn, is substantially heavier than Pu-238, in the isobaric triplate U-238, Np-238, Pu-238. This chemical method of investigation is particularly applicable to this isobaric triplate because there appears to be no other mechanisms to account for the Pu-238 should it be found.

3.6.30   LAMS-991. SPONTANEOUS FISSION OF PLUTONIUM-
          238. John Jungerman. December 19, 1949, Decl.
          Dec. 10, 1955

A 0.25 microgram sample of Pu-238 was obtained from Dr. J. G. Hamilton. Two samples were used of about 5 million alpha disintegrations per minute. The exact sample strength was 5.17×10^6 disintegrations per minute and 4.93×10^6 disintegrations per minute. The number of spontaneous fissions per gram times hours is less than 4.79×10^8/half life of Pu-238. Where the half life of Pu-238 is the half life of Pu-238 in years with a probable error of 10%. If the half life of Pu-238 for alpha activity is taken as 60 years, then this gives 7.96×10^6 F/gram hours or 2.22×10^3 F/gram seconds. * This result agrees within the error of the experiment with the value obtained at Los Alamos which was 2.1×10^3 F/gram seconds if the half life of Pu-238 is 60 years*. ((The term F stands for fissions.))

((*The 60 year value presented here is invalid. The presently accepted value for the half life of Pu-238 is 86.41 ± 0.3 years.))

3.6.31   ANL-4286.   SPONTANEOUS FISSION COUNTING OF URANIUM-236 AND PLUTONIUM-238.   A. H. Jaffey and A. Hirsch.   Argonne National Laboratory Summary Report January, February, March, 1949.   Chemistry Division Section C, May 12, 1949.   Decl with deletions Feb. 12, 1957, 15 pgs.   Page 42.

A sample containing 3.22×10^6 disintegrations per minute of Pu-238 was counted for 202 hours in which 72 spontaneous fission counts were observed. Using the value of 92 years for the Pu-238 half life, this counting rate corresponds to a sample content of 0.089 ± 0.003 micrograms. Since counts due to alpha pile up and neutron fission are negligible, this determination yields a value of $4.0 \pm 0.34 \times 10^6$ fissions per gram hour for Pu-238. The indicated errors are probable errors which are lower than the hitherto accepted value of $7.7 \pm 1.2 \times 10^6$ fissions per gram hours. The latter value was based upon an inaccurate value for Pu-238 half life of 60 years and should be corrected to the presently accepted value of 92 years. The correction gives forth the value of $5.0 \pm 0.8 \times 10^6$ fissions per gram hour which checks within experimental error with the value reported here. The plutonium was prepared by the reaction Np-237 (n, gamma) Np-238 and probably contained less than 10% Pu-239 by weight and a negligible amount of Pu-240. Since the Pu-239 spontaneous fission rate was negligible no correction was necessary.

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3. 6. 32   UCRL-1243.   THE SPECTROMETRIC DETERMINATION
             OF SOME BETA PARTICLE AND CONVERSION ELECTRON
             ENERGIES.   Grover Davis O'Kelley, A. B. Howard
             College, 1948.   Dissertation.   Submitted in partial
             satisfaction of the requirements for the degree of Doctor
             of Philosophy in Chemistry in the Graduate Division of the
             University of California.

Section E.   Radiations from Pu-243 and Pu-238.   The electron
capture in Am-242m has been shown to result in the long lived
plutonium isotope Pu-242 while the beta decay of Am-242 m forms
Cm-242.   If the plutonium fraction is separated from a sample of the
Am-241 which has been subjected to long neutron radiation, both Pu-
242 and Pu-238 are present in about equal amounts by weight, the
latter plutonium isotope resulting from alpha decay of Cm-242.   Alpha
pulse analysis in mass spectrographic measurements of these plutonium
samples showed the alpha particles energy of Pu-242 to be 4. 88 Mev
and the alpha particle half life to be approximately 5×10^5 years, in
good agreement with the alpha decay scheme systematics.   Energy
surface considerations in this region indicate beta stability for both
Pu-242 and Pu-238.   Recently the half life of Pu-238 has been
measured as 89. 59 ± 0. 37 years.   The alpha particle energy is 5. 47
Mev.

3. 6. 33   RANGE MEASUREMENTS OF ALPHA PARTICLES FROM
             THE 94^{239} and 94^{238}.   O. Chamberlain, J. W. Gofman,
             E. Segre and A. C. Wahal (Department of Chemistry and
             Physics, University of California, Berkeley, California).
             Physical Review 71, 529-30, April 1947

ABSTRACT

The ranges of alpha particles from 94^{239} and 94^{238} have been
measured by comparison with polonium alphas and are found to be
3. 68 centimeters and 4. 08 centimeters in air.

((End of Abstract))

To determine the ranges of alpha particles from 94^{239} and 94^{238} with
greater precision than previously reported a direct comparison of
these ranges with the ranges of alpha particles from polonium was
carried out.   The samples of 94 were deposited on platinum by
evaporation.   They were separated from the bombarded uranium with
a very small amount of carrier.   The uranium sample was electro-
plated on a copper disc.   The thinness of all these samples is borne
out by the small values of the straggling coefficient observed.

3.7   CURIUM-242

HALF LIFE

    (Alpha) 162. 46 days   Ref. 3. 7. 25 AERE C/R
                                   1373, Feb. 1954

    (S. F.) 7. 2 x 10^6 years   Ref. 3. 6. 24 Phys. Rev. 96,
                                   545-6, Oct. 1954

NEUTRONS/SPONTANEOUS FISSION

    2. 65 ± 0. 09   Ref. 3. 6. 19 Phys. Rev. 101,
                                   746-50, Jan. 1958

ENERGY LEVELS AND DECAY SCHEME

    Cm-242 $\xrightarrow{\text{ALPHA}}$ Pu-238

    Alpha   6. 115 (74. 0 ± 2)%   Ref. 3. 7. 3. J. Exptl.
    Energies   6. 071 (26. 0 ± 0.9)% Theoret. Phys. USSR 45,
    (Mcv)   5. 971 (0. 035 ±   1360-1371, Nov. 1963
                     0. 002)%
               5. 881 (0. 005)%
               5. 605 (4 x 10^{-5})%
               5. 515 (3 x 10^{-4})%
               5. 200 (1. 4 x 10^{-4})%

    Gamma   44. 0 (0. 041)%   Ref. 3. 9. 5. Rev. of Mod.
    Energies   100 (6 x 10^{-3})%   Phys. , Vol. 30, #2, pt. 2,
    (kev)   157 (2 x 10^{-3})%   April 1958
               210 ($\sim$2 x 10^{-5})%
               562 (1. 8 x 10^{-4})%
               605 (1. 4 x 10^{-4})%
               890 (9 x 10^{-6})%
               935
                  1. 01 ($\sim$ 10^{-5})%

Cm-242

	Mev	%
	5.200	(1.4×10^{-4})
	5.515	(3×10^{-4})
	5.605	(4×10^{-5})
	5.881	(0.005)
	5.971	(0.035)
	6.071	(26.0)
	6.115	(74.0)

0+ 935

(1-) 605

(8+) 511.0

(6+) 301.0

(4+) 144.0

2+ 44.0

0+

Pu-238
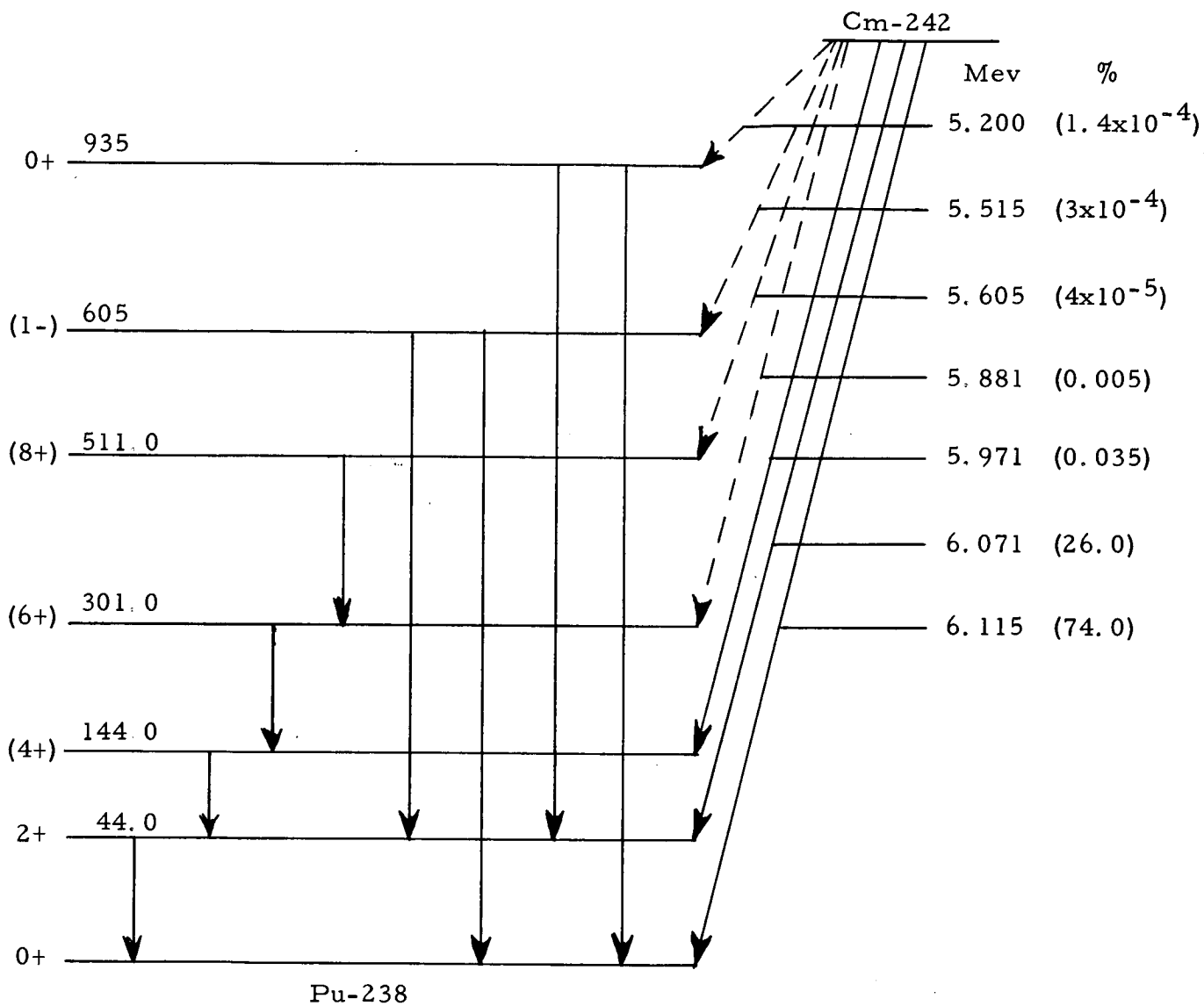
Ref. 3.9.1, also 3.9.8.

MNSP-VT-4017 Sept. 15, 1964
Rev. Mod. Phys. Vol. 30 #2 pt II
April 1958

3.7.1   ISOTOPIC POWER DATA SHEETS.   S. J. Rimshaw (Oak
         Ridge National Laboratory, Oak Ridge, Tennessee).   For
         presentation at Industry Information Meeting on Isotopic
         Power Development and Applications, Washington, D.C.
         May 18-19, 1964

Source Material	Cm_2O_3
Half-Life	162.5 days
Decay and Radiation Properties	$Cm-242 \longrightarrow Pu-238$ $(T_{1/2} = 89.6$ years$)$ Alphas Gammas 6.110 Mev (73.7%) 44.2 kev (26.3%) 6.066 Mev (26.3%) Spontaneous fission half-life of Cm-242 = 7.6×10^6 years
Isotopic Composition	$>98\%$ Cm-242.
Activity Concentration	3044 curies per gram of Cm-242$_2O_3$; 1218 curies per gram of product (0.4 grams of Cm-244$_2O_3$ + 0.6 grams of Am-241O$_2$.)
Radiochemical Purity	$>99\%$
Chemical Purity	40% or less. About 60% Am-241 $(T_{1/2} = 462$ years$)$ will be present.
Specific Power	44.1 watts per gram of Cm-Am oxides (approximate composition - 40% Cm-242 and 60% Am-241), or 36.1 watts per kilocurie of Cm.
Density	Theoretical density is 11.2 g/cm^3. Practical density is $\sim$9.0 g/cm^3 ($\sim$80% of theoretical density).
Power Density	397 watts/cm^3 for Cm-242$_2O_3$ (40% Cm - 60% Am) with a density of 9 g/cm^3. About 0.5% of the total power will be contributed by Pu-238 and Am-241.

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Thermal Conductivity	0.028 watts/cm·oC at 125°C (based on Gd_2O_3)
Coefficient of Expansion	$10.5 \times 10^{-6}/°C$ (25° to 1000°C) (based on Gd_2O_3)
Melting Point	1950°C in helium
Mechanical Properties	Modulus of elasticity (sonic) 14.5×10^6 lb/in^2 at 25°C (based on Gd_2O_3)
Thermal and Radiation Stability	No data available.
Radiation Attenuation	Shielding required for gamma radiation is small compared to the neutron shielding required. Neutron dose rate is 0.1 rad/hr at 50 cm for a 2000 thermal watt source shielded with 10 cm of LiH. Additional data are available in ORNL-TM-591 (Rev.) and in ORNL-3576.
Gas Evolution Due to Radioactive Decay Processes	Helium accumulates as a result of α decay. An original 1000-curie source of Cm-242 will produce 13.9 cm^3 of He in 162.5 days (1.0 half-life)
Leach Rate	No data available
Vapor Pressure	No data available
Resistance to Thermal Shock	No data available
Burnup Characteristics	Dispersibility Poor
Capsule Compatibility	No data available

3.7.2   ALPHA DECAY OF CURIUM ISOTOPES.   B. S. Dzhelepov, R. B. Ivanov, E. G. Nedovesov, and V. P. Chechev, J. Exptl. Theoret. Phys. USSR 45, 1360-1371, November 1963. ((Translated in Soviet Physics JETP, Vol. 18, No. 4, April 1964))

The alpha spectra of the Cm-242-246 isotopes are investigated with a pi $\sqrt{2}$ magnetic alpha spectrometer. The energies and intensities of the alpha transitions are determined precisely. A possible interpretation of some excited Pu-239 and Pu-241 states resulting from the alpha decay of Cm-243 and Cm-244 are discussed on the basis of the Nilsson model. Decay schemes for Cm-242-246 are presented.

((End of Abstract))

The sources used for measurement of the alpha spectra were prepared by vacuum deposition of active material on glass. In the different runs the dimensions of the sources varied from 0.1 x 10 to 1 x 15 millimeters depending upon the particular experiment. ((Table 1 of this work presents transition energy intensities, and energy levels, for Cm-242 through 246. This table is reproduced in part for Cm-242 and Cm-244. The decay schemes for Cm-242 and Cm-244 are presented as Cm2-1. The 514 and 305 kev levels shown in Figure Cm2-1 were not identified by these investigators but were taken from other references.))

3.7.3   *LONG-RANGE ALPHA PARTICLES IN THE SPONTANEOUS FISSION OF TRANSURANIC ELEMENTS. N. A. Perfilov, Z. I. Solov'eva, R. A. Filov, and G. I. Khlebnikov.   p. 145-50 of "Fizika Deleniya Atomnykh Yader".   Moscow, Gosatomizdat, 1962.

Investigations were made of spontaneous fission in the transuranic region accompanied by the emission of long-range alpha particles. The samples used were Cm-242 and Pu-240. The alpha particles were detected using emulsions. Energy spectra were obtained for alphas whose energies were greater than 13 Mev. The maxima in these spectra occurred at 15.5 ± 1.0 Mev for Cm and at 17.0 ± 0.5 Mev for Pu. The spectra were extrapolated to lower alpha energies by assuming that the distributions were Gaussian. In this way ratios were determined for the probability of fission accompanied by alphas as compared to the probability for ordinary binary fission. These ratios were: 1/280 ± 50 for Cm-242 and 1/400 ± 60 for Pu-240. These numbers were compared with the ones published for Cf-252. It was found that the published Cf-252 values vary substantially among themselves.

3.7.4   ENERGY OF ALPHA PARTICLES FROM SOME CURIUM ISOTOPES.   R. B. Ivanov, A. S. Krivokhatskii and B. G. Nedovesov, Izvestia Akad Nauk, USSR 26, 976-8, August 1962

TABLE 1

Lines in Figures	Transition Energy (kev)	Energy Lever (kev)	Transition Intensity (%)
		CURIUM-242	
1	6115 ± 1	0	74.0 ± 2.0
2	6071 ± 1	44	26.0 ± 0.9
5	5971 ± 1	146	0.035 ± 0.002
		CURIUM-244	
8	5906 ± 3	0	76.2 ± 2.0
10	5763 ± 3	43	23.8 ± 0.9
13	5666 ± 3	142	0.021 ± 0.002
19	5515 ± 4	292	0.003 ± 0.001
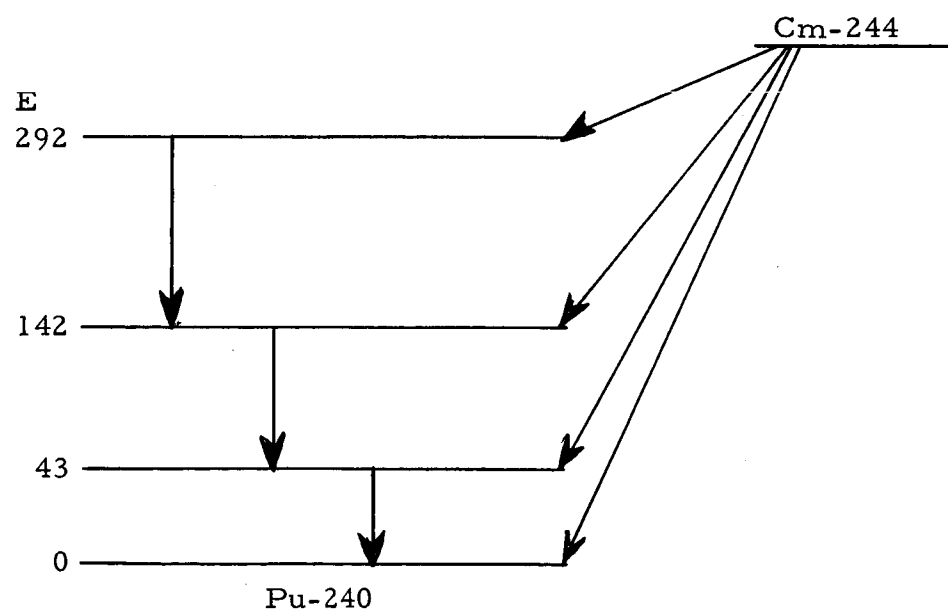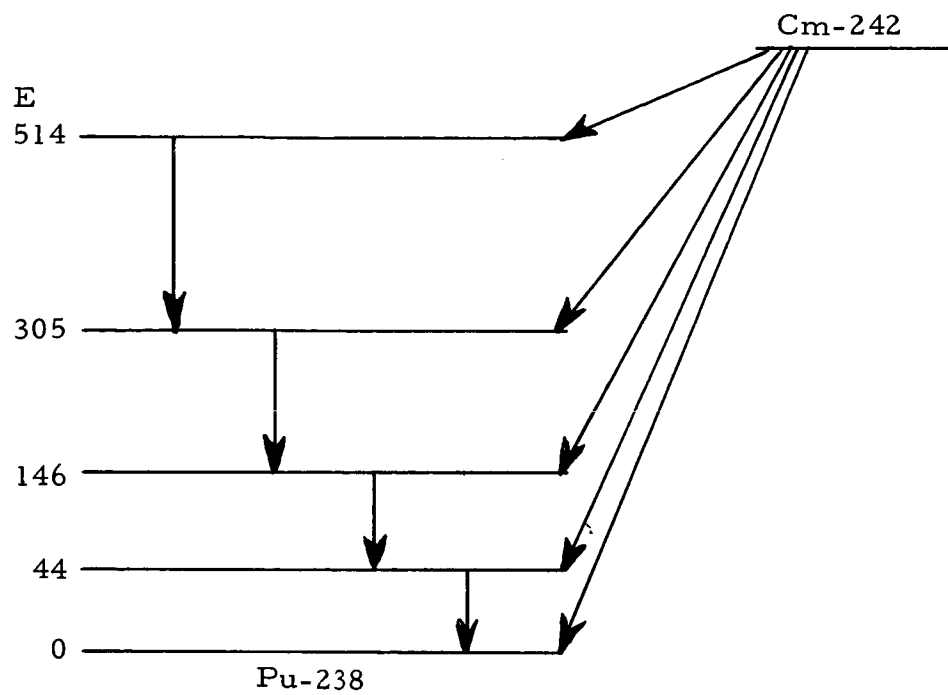
FIGURE Cm2-1. DECAY SCHEMES FOR Cm-242 AND Cm-244

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((In this effort the authors determine the energies of alpha particles from Cm-242, 243, 244 by comparing their energies with the energies of alpha groups from Bi-212.))

Bi-212.   The measurements were carried out on the double focusing magnetic alpha spectrometer.   For determining the energy of the alpha particles from Cm-242 we carried out four series of measurements.   In each of these the photographic plate was exposed first to the curium activity and then to the Bi-212 source.   The strength of the magnetic yield in each series of measurements was kept constant to within 0.01%.   The values of the energy of the two alpha groups from Cm-242 together with the average values taken from references 2, 4, and 5 are shown in Tables I and II as follows:

TABLE I.   ENERGY OF ALPHA TRANSITIONS
IN Cm-242 (kev)

Series #	α_o	α_i
1	6114.0	6070.4
2	6115.0	6071.0
3	6115.4	6071.5
4	6114.5	6070.2
Mean	6115 ± 1	6071 ± 1
Data of other Ref.	6110 ± 4	6066

TABLE II.   ENERGY OF ALPHA TRANSITIONS
IN Cm-244 (kev)

Series #	α_o	α_i
1	5805	5763
2	5806	5763
Mean	5806 ± 2	5763 ± 2
Data of other Ref.	5801 ± 2	5759

((References 2, 4, and 5 refer to past work in this field.))   From the basis of our data on the alpha particle groups we were able to determine

the energy of the transition with an intensity of 0.035% in Cm-242. Our calculations yielded a value of 5971 kev. The energy of the Cm-244 alpha-2 line was determined in the same way as for Cm-242. It proved to be equal to 5666 kev.

3.7.5   LONG RANGE PARTICLES FROM NUCLEAR FISSION. Ralph A. Nobles (University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico). Physical Review 116, 1508-1513, May 1962

ABSTRACT

A measurement of the probability of emission of long range particles which are known to be predominantly alpha particles made with a multiple ionization chamber gave the following rates for spontaneous fission ((only those of interest are presented)) Cm-242, 257 ± 17, Cm-244, 314 ± 20. ((The balance of this abstract is concerned with isotopes not of interest to this section and has been omitted.))

3.7.6   A SURVEY OF RESEARCH ON THE TRANSURANIC ELEMENTS. M. B. Waldron (Metallurgy Division AERE, Harwell). Contemporary Physics 2, 385-402, June 1961

((This article presents an historical review of work done since 1940 on the transuranic elements. It reviews in part the properties of Cm-242, 244, and Pu-238. It presents half life values, disintegration products, etc., but does not present any detailed references on these figures. This article may be of some interest to those wishing to have a complete, or detailed picture on the history of the physics of these elements.))

3.7.7   FLUORESCENCE AND OTHER YIELDS IN THE L_{II} SHELL IN PLUTONIUM. L. Salgueiro, J. G. Ferreira, J. J. H. Park, and M. A. S. Ross (Department of Natural Philosophy, University of Edinburgh). Proceedings of the Physical Society (London) 77, 657-64, March 1961

ABSTRACT

A study has been made of the L, X-radiations emitted after disintegration of Cm-242 to determine as accurately as possible the fluorescence and other yields of the L_{II} subshell in plutonium. Observations have been made on the total intensity per disintegration

of the L, X-rays by observing the L, X-ray photons in coincidence with alpha particles from Cm-242. On the relative intensity of the L, X-rays from the L_{II} and L_{III} subshells the sensitivity of the curve crystal spectrograph used for the latter observations had previously been determined. The experimental results are: fluorescence yield, $w_2 = 0.413 \pm 0.02$, Coster-Kronig yield $F_{2,3} = 0.22 \pm 0.08$, and Auger yield $A_2 = 0.37 \pm 0.08$. The total fluorescence yield of the L shells is $w = 0.486 \pm 0.01$. The values of w_2 and w are independent of previous work on fluorescence yields but for the distribution of yields between $F_{2,3}$ and A_2, it was necessary to use an extrapolated value of $w_3/$

3.7.8 ++AERE-R-3209. COLLECTED INDEPENDENT FISSION YIELDS FOR THERMAL NEUTRON FISSION OF U-233, Pu-239, and U-235, 14 MEV NEUTRON FISSION OF U-235, PILE NEUTRON FISSION OF U-238, Th-232, AND Am-241, AND SPONTANEOUS FISSION OF Cm-242. I. F. Croall, comp. Jan. 1960, 9 p. BIS. (United Kingdom Atomic Energy Authority, Research Group. Atomic Energy Research Establishment, Harwell, Berks, England)

3.7.9 REFER TO 3.6.10. ENERGY LEVELS OF Pu-238 AND Pu-239 NUCLEI-SOVIET RESEARCH ON THE LANTHANIDE AND ACTINIDE ELEMENTS 1949-1957. PART III. Nuclear Chemistry and Nuclear Properties, New York Consultants Bureau, Inc. 1959.

3.7.10 ZEEMAN INVESTIGATIONS OF CURIUM-242. J. C. Hubbs, R. Marrus and J. O. Winocur (Radiation Laboratory and Department of Physics, University of California, Berkeley, California). Physical Review 114, 586-9, April 1959

ABSTRACT

The atomic beam magnetic resonance method has been used to investigate 163-day Cm-242. The spin of this even-even nuclide is found to be zero. Four low lying electronic energy levels are found and the Lande factors are measured to be $g_{J2} = 2.561 \pm 0.003$, $g_{J3} = 2.000 \pm 0.003$, $g_{J4} = 1.776 \pm 0.002$ and $g_{J5} = 1.671 \pm 0.003$. No direct measurement can be made of the angular momenta of these levels but other considerations contained in the text make probable the J values indicated in subscripts and arising from the electronic configuration $(5 f)^7 (6 d)^1 (7 s)^2$.

3. 7. 11   NUMERICAL SOLUTIONS OF THE CURIUM-242 ALPHA-
DECAY WAVE EQUATION.   John O. Rasmussen
(Department of Chemistry and Radiation Laboratory,
University of California, Berkeley, California), and
Eldon R. Hansen (Radiation Laboratory, University of
California, Berkeley, California).   Physical Review
109, 1656, March 1958

ABSTRACT

Numerical integration of the previously derived alpha-decay wave
equation, including electric quadrupole coupling terms, was carried
out for Cm-242 including $1 = 0$, 2, 4, and 6 partial waves.   Eight
integrations were carried inward in spherical polar coordinates on an
IBM-650 computer with different initial conditions, such that a
complete set of eight linearly independent solutions to the system of
coupled equations was generated.   Eight different linear combinations
of this base set were found which satisfy the boundary conditions
imposed by experimental Cm-242 alpha-group intensities.   Wave
amplitudes on a spherical surface near the nucleus are given for all
eight cases, and the radial variation throughout the barrier region is
given for two cases.   The matrix formalism of Froman is employed
in another presentation of the results, and a comparison is made with
the analogous Froman matrix.   By using a modified Froman matrix
together with our results, the alpha-wave distributions are calculated
for a spheroidal nuclear interaction surface.   A discussion is made
of conditions for the existence of solutions satisfying boundary
conditions imposed by alpha-group intensities, and the quadrupole
phase shift problem is considered.

3. 7. 12   ALPHA DECAY OF Cm-242.   L. N. Kondrat'ev, V. B.
Dedov, and L. L. Gol'din, Izvestia Akad Nauk, USSR 22,
99-100, February 1958

((The purpose of this experiment was the calculation of the intensity
of the alpha decay of Cm-242 to the second excited level (4+) and the
comparison of the calculated and experimental values.   The results
of the experiments purported to show that the pronounced divergence
between the experimental and calculated values of the intensity of
alpha decay to the (4+) level actually exist.   Table 1, not reproduced
here, presents excitation levels of alpha particles of Cm-242,
intensities in per cent, and spin and parities.))

3.7.13   REFER TO 3.6.15.   HALF LIFE OF Pu-238.   Journal
           of Inorganic and Nucl. Chem. 5, 6-11, 1957

3.7.14   THE ENERGY LEVELS OF Cm-242 NUCLEI.   S. A.
           Buranov and K. N. Sblyugin, Soviet Journal of Atomic
           Energy 1, 51-65, 1956

The alpha decay half life of the isotope Cm-242 is equal to 162.5 days.
According to Asaro and others it seems that the alpha spectrum
consists of four mono-energetic groups of alpha particle.   There
exists no information in the literature on the electron spectrum of
Cm-242.   ((The balance of the article is devoted to a detailed
analysis of the decay scheme of Np-239 and Np-238.   Included are
several figures depicting the beta spectrum of neptunium, the
spectrum of conversion electrons, nuclear energy levels, Curie plots,
etc.   As a part of the discussion on neptunium some information is
given on the characteristics of Cm-242 and Pu-238.))

3.7.15   REFER TO 3.6.17.   GAMMA RADIATION FROM THE
           DECAY OF PLUTONIUM-238 AND CURIUM-242.   Phil.
           Mag. 1, 981-1002, Nov. 1956

3.7.16   REFER TO 3.6.18.   FIRST EXCITED STATES OF
           HEAVY EVEN-EVEN NUCLEI.   Phys. Rev. 103, 1590-1,
           Sept. 1956

3.7.17   ALPHA DECAY OF SPHEROIDAL NUCLEI.   John O.
           Rasmussen (Radiation Laboratory and Department of
           Chemistry, University of California, Berkeley,
           California), and Benjamin Segall (Radiation Laboratory,
           University of California, Berkeley, California).   Physical
           Review 103, 1298-1308, September 1956

ABSTRACT

The consequences of spheroidal deformation of nuclei on the barrier
transmission in alpha decay are considered.   A set of coupled
differential equations is derived relating the amplitudes of the various
groups of alpha particles emitted from a nucleus described by the
Bohr-Mottelson model.   The cases of the decay of Th-228 and Cm-242
were studied numerically and from them information regarding the
probability distribution of alpha particles on the nuclear spheroidal
surface is observed.   It is found that the one body model of an alpha

particle in a well does not yield these distributions and it is thus concluded that alpha particle clusters have a short mean free path in nuclear matter. The shift in the surface distributions of Th-228 and Cm-242 may be explained qualitatively in terms of the order of nucleon orbital filling. The over-all penetration factors for the spheroidal case are compared with those for the spherical case. It is found that the resultant enhancement due to the deformation is not nearly as large as that predicted by Hill and Wheeler on the basis of one dimensional approximation. ((The entire article is devoted to theoretical work, no experimentation is performed.))

3.7.18   UCRL-3456.   ALPHA DECAY STUDIES IN THE HEAVY ELEMENT REGION.   John Phillip Hummel (University of California, Radiation Laboratories, Berkeley, California) July 3, 1956

Under Table of Contents III.   Experimental Results, B. Gamma rays in the decay of Cm-242, page 42, and C. Alpha Decay of Cm-244, page 45.

ABSTRACT

Using primarily a 75 centimeter radius of curvature 60°, symmetrical electron magnetic analyzer, the study of the complexity of the following alpha spectra were made: E-253, Cf-246, Cm-244, Am-243, Pu-236, 242, Pa-231, Th-227, 230, Ae-225, At-209, Po-206. An investigation of the gamma rays associated with the following isotopes was also made, Cf-246, Cm-242, 244, Am-243, Pu-236, 242. The abundances of the three gamma rays of Cm-242 were measured. These abundances are as follows: 2.9×10^{-4} (44 kev gamma ray) 4.1×10^{-5} (100 kev gamma ray) and 1.8×10^{-5} (155 kev gamma ray). These abundances are all smaller than those given by Asaro. One notes, however, that the relative abundances of the three gamma rays are the same in both studies. These smaller intensities yield somewhat larger conversion coefficients for the 44 and 100 kev gamma rays than given by Asaro, et al. However, the previous interpretation of these conversion coefficients in terms of gamma ray multi-polarities is not altered by the new intensity.

3.7.19   CONVERSION ELECTRON SPECTRA OF Cm-242 AND Cm-244.   W. G. Smith and J. M. Hollander (Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California). Phys. Rev. 101, 746-50, Jan. 1956

ABSTRACT

The conversion electron spectra of Cm-242 and Cm-244 have been studied by means of two 180° photographic recording beta-ray spectrographs. Conversion coefficient ratios in the L and M subshells have been measured for several E2 transitions in the decay of these nuclides, and the values so obtained compared with theoretical ratios. Accurate energy determinations of the first three excited states in Pu-238 are reported, and the validity of the Bohr-Mottelson rotational energy formula, including the vibration-rotation interaction term to describe these states, is discussed. A more accurate value is reported for the energy of the first excited state in Pu-240. The decay of I-131 is discussed briefly.

((End of Abstract))

3.7.20   REFER TO 3.6.19.   PROBABILITIES OF PROMPT
         NEUTRON EMISSION FROM SPONTANEOUS FISSION.
         Phys. Rev. 101, 1016-20, Jan. 1956

3.7.21   CONVERSION ELECTRON SPECTRA OF Cm-242 and
         Cm-244.   W. G. Smith and J. M. Hollander (Radiation
         Laboratory and Department of Chemistry, University of
         California, Berkeley, California).   Physical Review 99,
         47-55, July 1955

ABSTRACT

The conversion electron spectra of Cm-242 and Cm-244 have been studied by means of 2, 180° photographic recording beta ray spectrographs. Conversion coefficient ratios in the L and M subshells have been measured for several E2 transitions in the decay of these nuclides, and the values so obtained compared with theoretical ratios. Accurate energy determinations of the first three excited states in Pu-238 are reported, and the validity of the Bohr-Mottelson rotational energy formula including the vibration rotation interaction term to describe these states is discussed. A more accurate value is reported for the energy of the first excited state in Pu-240. The decay of I-131 is discussed briefly.

((End of Abstract))

The spectrograph sources were prepared by electro deposition of the active materials upon 10 mil or 14 mil platinum wires using a proce-

dure suggested by B. G. Harvey in which M (OH)$_3$ (where M is the actinide cation) is deposited on the wire cathode of an electrolysis cell using NH$_4$ HS $_4$ at a pH of 3.6 as the electrolyte. A decay scheme for Cm-242 is presented in Figure 4 of this article and is reproduced as Figure Cm2-2.

3.7.22 REFER TO 3.6.23. NUCLEAR PROPERTIES OF THE PLUTONIUM ISOTOPES. McGraw Hill Pub. Co. 1954

3.7.23 UCRL-2932. DECAY CHARACTERISTICS OF SOME HEAVY ISOTOPES. Isador Perlman, Frank Asaro, Frank S. Stephens, John P. Hummel, and Richard C. Pilger (University of California Radiation Laboratory Chemistry Division Quarterly Report December 1954 - January, February 1955). page 59.

Curium-242. The energy of the E2 transition between the first excited state and ground state of Pu-238 has been determined to be 44.11 ± 0.04 kev from measurement of 7 conversion lines. We have also observed the internal conversion coefficient ratios L_{II}/L_{III} = M_{II}/M_{III}; M_{II}/M_{III} = 1.2 in good agreement with the theoretical value of 1.2 calculated for the L_{II}/L_{III} ratio.

3.7.24 REFER TO 3.6.24. CORRELATION OF SPONTANEOUS FISSION HALF LIVES. Phys. Rev. 96, 545-6, Oct. 1954

3.7.25 UCRL-2547. SOME CHEMICAL PROPERTIES OF CURIUM. Darrell Charles Feay (University of California Radiation Laboratory). Thesis, April 12, 1954. III Gamma Radiation from Cm-242, page 15.

A sample of curium, see Table I, was prepared for the investigation of the electron spectra from gamma radiation using a double focusing beta ray spectrometer.

TABLE I

Spectrographic Analysis of Sample

Am	0.5% (by weight)
La	0.2
Fe	0.1
Al	0.4
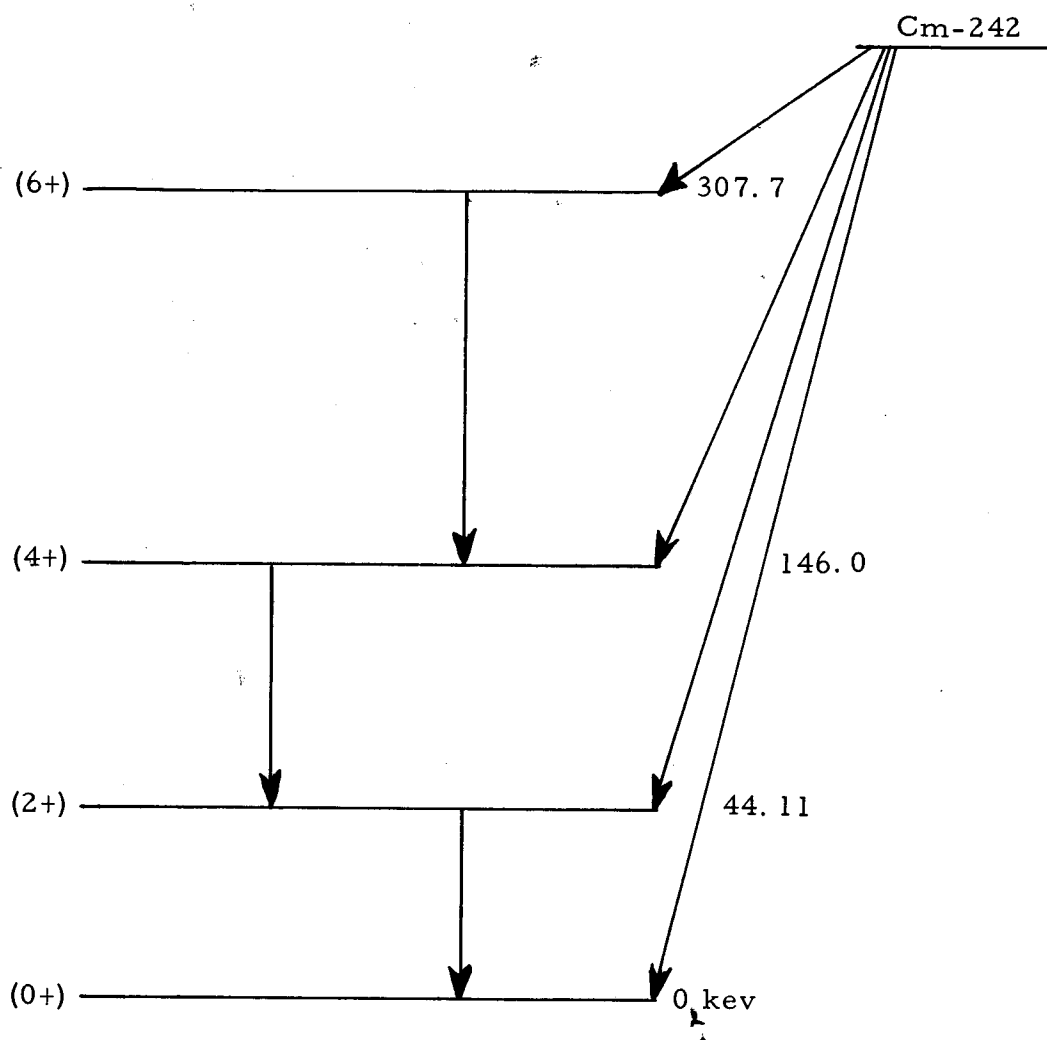
FIGURE Cm2-2.   Cm-242 DECAY SCHEME

The energies and $L_1 + L_2 = L_3$ conversion ratios were determined for the two most abundant transitions of 44.1 and 102.0 kev, respectively. Previous work by F. Asaro on total conversion coefficients gives strong evidence that both are of E2 character. Since the $L_1 + L_2 = L_3$ ratio narrows the possibilities to E1 or E2 for the 44.1 kev gamma ray and to E2 only for the 102.0 kev gamma ray we may consider the E2 character confirmed. Thus, the decay scheme of Cm-242 is as shown in Figure 1 ((presented as Figure Cm2-3)). Some hint of the previously reported 157 kev radiation in this decay was found but remains to be confirmed with a sample of greater intensity.

3.7.26   AERE C/R-1373. THE HALF LIFE OF CURIUM-242.
         Mrs. K. M. Glover and J. Milsted (Atomic Energy
         Research Establishment, Department of Atomic Energy,
         Harwell, Berks). Feb. 1954

The half life of Cm-242 has been redetermined by accurate alpha counting of a pure curium source over a period of 7 months, after allowing for the growth of the Pu-238 daughter. The value obtained, 162.46 days is in very close agreement with the accepted value of 162.5 ± 2 days, but the precision has been greatly improved. The standard deviation of the half life from the present results; ± 0.27 days. The curium was produced by the neutron radiation of americium in a pile and was separated from the americium by the following steps: The precipitation as a fluoride with residual americium from a solution from which most of the americium has been oxidized to the fluoride soluble hexavalence state. This was repeated a second time with a reduction of volume. Elution from a zee-karb 225 cation exchange column with 11 normal hydrochloric acid to separate from rare earths. Elution from a similar cation exchange column from 0.25 molar curium nitrate solution adjusted to pH 3.50 carried out at 87° centigrade. The early fractions from the second elution showed no detectable activity, alpha type, other than that of Cm-242 (6.11 Mev). The later results obtained with a proportional gamma counter indicated a maximum americium 241/Cm-242 alpha activity ratio of 10^{-4}. An aliquot containing about 2×10^7 alpha disintegrations per minute was placed on a polished platinum disc, evaporated to dryness, and ignited to about 800° centigrade. The resulting source was practically weightless.

3.7.27   AERE C/R-1365. A CALORIMETRIC DETERMINATION
         OF THE HALF LIFE OF CURIUM-242. W. P. Hutchinson
         and A. G. White (Atomic Research Establishment,
         Department of Atomic Energy, Harwell, Berks), Jan. 1954
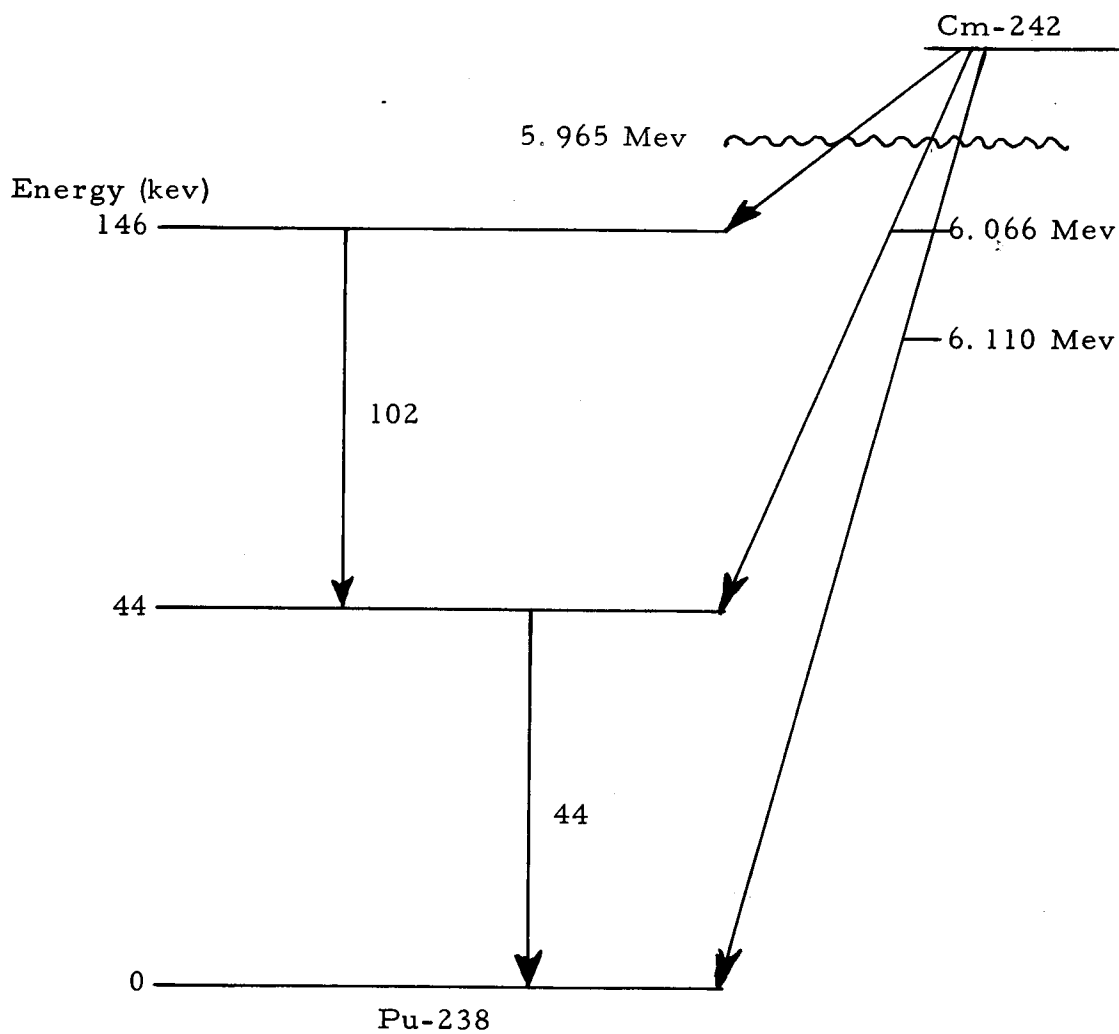
FIGURE Cm2-3.   DECAY SCHEME FOR Cm-242.

Calorimetric measurements on a 2 microgram sample of Cm-242 have
confirmed the value of 162.5 days previously published for the half
life of this nuclide. The currently accepted value for the half life of
this nuclide is the value of 162.5 ± 2 days, determined by Hanna using
a counting procedure on samples from which the Am-241 used for
radiation had not been separated.

3.7.28   AECU-2757. ANGULAR CORRELATION AND COINCI-
DENCE STUDIES OF ALPHA GAMMA CASCADES FROM
Cm-242, Pa-231, and Am-241. Richard Lee Moore, A.B.,
MA, Dissertation presented in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
Graduate School of the Ohio State University (The Ohio
State University 1953)

Under Table of Contents: Chapter 4, Cm-242 Experiments, page 107,
4.1 decay scheme. Cm-242 and Cm-243 have been studied by Asaro.
His proposed decay scheme for Cm-242 is shown in Figure 36**.
Cm-243 is known to be a prolific emitter of K, X-rays. In the present
experiment there was a sufficient amount of Cm-243 present for its
K, X-rays to obscure the 100 kev radiation from the second to the
first excited state of Cm-242 4.2 source. The source used was
evaporated from a 2 molar hydrochloric acid solution onto a thin nylon
backing on a circular wire frame about 10 millimeters inside diameter.
The diameter of the sources which could be judged from the area of
discoloration was not greater than 3 millimeters. The decay rate
was 4.0×10^7 disintegrations per minute, about 18 microcuries. This
rate included the Cm-243 disintegrations whose alphas were estimated
to have a relative abundance of not greater than 1%. The source was
not as thick for the alphas as the Pa source and gave an alpha particle
energy resolution of 18%. However, this was poorer than that
obtained from the thin Pu-239 source.

((**Shown in 3.7.29 below.))

3.7.29   THE ALPHA SPECTRA OF Cm-242, Cm-243 AND Cm-244.
Frank Asaro, S. G. Thompson and I. Perlman (Radiation
Laboratory, Department of Chemistry, University of
California, Berkeley, California). Physical Review 92,
694-702, November 1953. ((Also published as UCRL-2193,
Ref. 3.7.32.))

ABSTRACT

The alpha and gamma spectra of Cm-242, Cm-243, and Cm-244 have been studied with an alpha particle spectrograph and gamma ray scintillation counter. Cm-242 has alpha groups of 6.110 (73.7%), 6.066 (26.3%) and 5.964 Mev (0.035% and gamma rays of 44 (0.041%), 100 (0.006%) and 157 kev (0.0027%). Cm-243 has alpha groups of 5.985 (6%), 5.777 (81%) and 5.732 Mev (13%) and gamma rays of 104, 226 and 278 kev in coincidence with the 5.777 Mev alpha group. Cm-244 has alpha groups of 5.798 (75%) and 5.755 Mev (25%). The spectra are discussed relative to alpha decay theory and corresponding excited states reached by beta minus decay processes.

((End of Abstract))

All samples which were used as sources in the spectrograph were prepared by vacuum sublimation. After chemical purification, each sample of curium present in solution as the chloride was evaporated to dryness on a tungsten ribbon. Under vacuum, current was passed through the tungsten ribbon and the curium sublimed onto the two mil thick platinum plate masked to a band 1" x 0.12". When placed in the spectrograph the sample was made to approximate a line source by placing before it a stainless steel plate with a devining slit 1" x 0.018" or 1" x 0.005". ((Article goes into fine detail in a description of the principal alpha groups of Cm-242, Cm-244 and the low energy alpha groups of Cm-242 and the alpha spectrum of Cm-243. Descriptions of decay schemes for Cm-242, 243, and 244 are described. The decay scheme for Cm-242 and Np-238 is presented as Figure 6. Figure 6 is shown here as Figure Cm2-4.))

3.7.30   ANL-5024 REVIEW, RADIO CHEMICAL INVESTIGATION
OF THE SPONTANEOUS FISSION OF CURIUM-242,
Summary Report - October, November, and December 1952.
Compiled by J. R. Gilbreath and O. C. Simpson, August
14, 1953. (Argonne National Laboratories, Chemistry
Division.) Section 3, Radio Chemistry, page 55. L. E.
Glendenin and E. P. Steinberg.

The measurements of the spontaneous fission yields of Cm-242 have been refined and extended and a relatively complete radiochemical yield mass curve has now been established. The data are presented in Table XIII and the total change yields are presented graphically in Figure 14, with the fission yield mass curve for pile neutron fission of
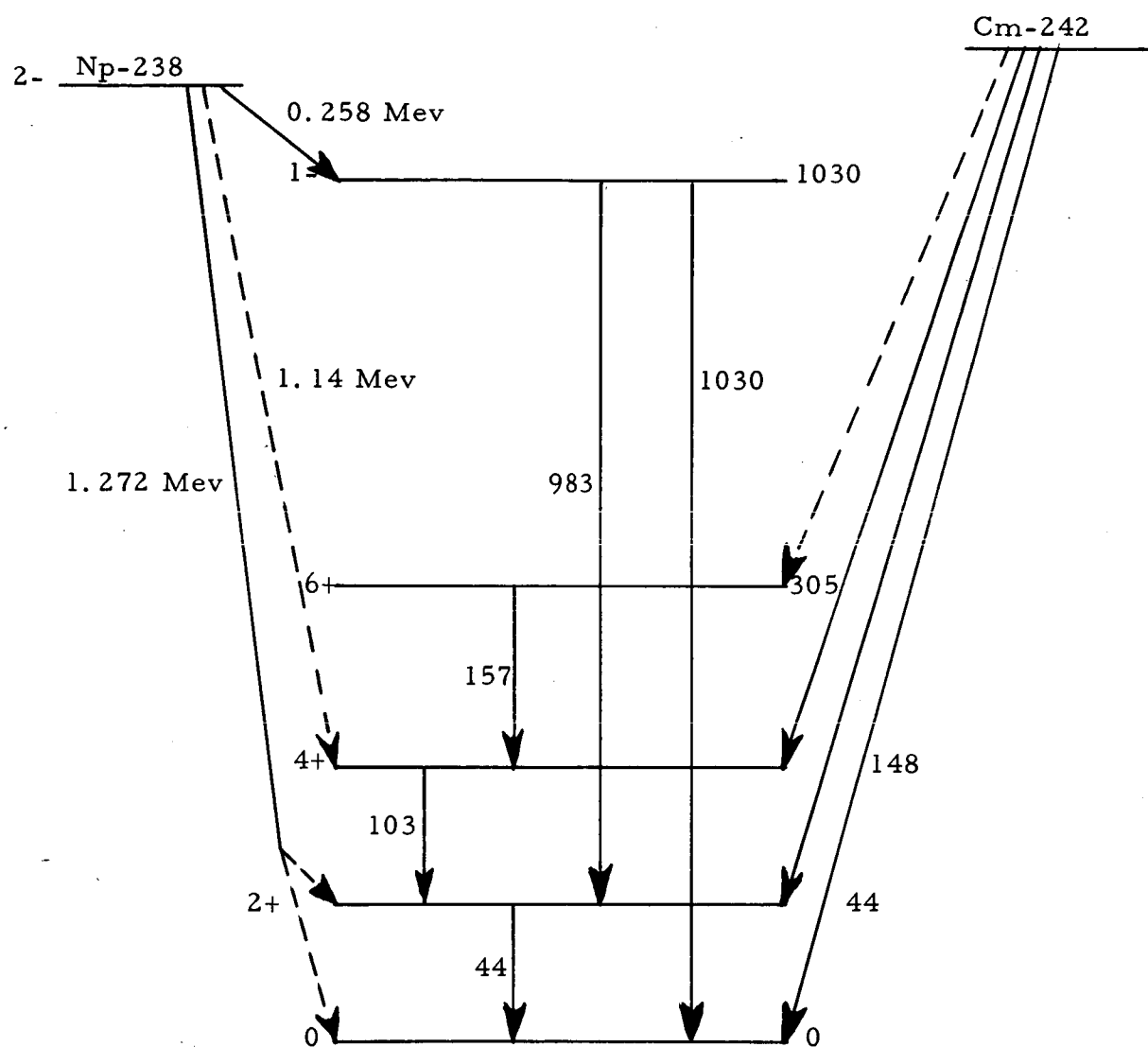
FIGURE Cm2-4.   DECAY SCHEMES FOR Cm-242 and Np-238

Pu-239 shown for comparison and suggested by the previous results. ((Figure 14, not shown here, presents yield mass curves for spontaneous fission of 242.))

TABLE XIII

Spontaneous Fission Yield of Cm-242 (half lives are in hours unless otherwise indicated).

Sr-91, 9.7; Sr-92, 2.7; Mo-99, 67; Ru-103, 40 days; Ru-105, 4.4; Ru-104, 1.0 year; Pd-109, 13.1; Pd-112, 21; Cd-115, 2.33 days; Cd-117, 2.83; Sb-127, 93; Sb-129, 4.2; Te-131m, 30; Te-132, 77; I-131, 8.0 days; I-133, 21; I-134, 52.5 min; I-135, 6.7; Cs-136, 13.7 days; Ba-139, 85 min; Ba-140, 12.8 days.

3.7.31   THE AVERAGE NUMBER OF NEUTRONS EMITTED IN THE SPONTANEOUS FISSION OF Cm-242.   F. R. Barclay and W. J. Whitehouse (Atomic Energy Research Establishment, Harwell, Didcot, Berks).   Proceedings of the Physical Society (London) A66, 477-53, May 1953

ABSTRACT

The average number of neutrons emitted in the spontaneous fission of Cm-242 has been measured by a method depending upon the device of counting only those neutrons which are detected after the occurrence of a fission.   In this way the affect of neutrons from sources other than spontaneous fission is eliminated.   The value found for V is 3.0 neutrons per fission.   The estimated standard error is 10-15%.

((End of Abstract))

The curium used in the experiment was prepared in pile irradiation of Am-241 which was believed to be isotopically pure.   The irradiation was comparatively short and only about 2×10^{-3} of the Am-241 was converted.   The separation of curium from americium and plutonium was carried on in an ion exchange column and was not complete. Analysis of the product showed that only 92.2-99.7% of its alpha particle activity was due to Cm-242.

3.7.32   UCRL-2193.   THE ALPHA SPECTRA OF CURIUM-242, CURIUM-243 AND CURIUM-244.   Frank Asaro, S. G. Thompson, and I. Perlman.   (University of California Radiation Laboratory) April 23, 1953

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All samples which were used as sources in the spectrograph were prepared by vacuum sublimation. After chemical purification each sample of curium present in solution as the chloride was evaporated to dryness on a tungsten ribbon. Under vacuum, current was passed through the tungsten ribbon and the curium sublimated onto a 2 mil thick platinum plate masked to a band one inch by 0.12 inch. When placed in the spectrograph, the sample was made to approximate a line source by placing before it a stainless steel plate with a defining slit one inch by 0.018 inch or one inch by 0.005 inch.

3.7.33 ANL-5000 (Del). MASS DISTRIBUTION IN THE SPONTANEOUS FISSION OF CURIUM-242. L. E. Glendenin, E. P. Steinberg, Summary Report for July, August and September 1952. Chemistry Division, Section C-11. Report compiled by J. R. Gilbreath, and O. C. Simpson (Argonne National Laboratory), page 55, January 21, 1953

Section III Radio Chemistry. The distribution of mass in the spontaneous fission of Cm-242 has been investigated by a radio-chemical determination of the fission yields of 14 nuclides ranging in mass from 91 to 140. The products of spontaneous fission were isolated by standard radiochemical procedures from solution of 1.0 and 1.5 milligrams of 162.5 days Cm-242, emitting 7.37×10^{12} alpha disintegrations/minutes/milligrams and giving 4.66×10^3 spontaneous fissions/minutes/milligrams. Isolations of the elements of interest were carried out after appropriate periods of growth from known amounts of Cm-242. The results are shown in Table 10. ((Table 10 gives the following information))

> Fission yields in the spontaneous fission of Cm-242:
> Sr-91, 1.0 ± 0.3; Sr-92, 1.1 ± 0.3; Mo-99, 6.1 ± 0.6;
> Ru-105, 9.8 ± 0.6; Pd-109, 3.0 ± 0.3; Pd-112, 1.0 ± 0.1;
> Cd-115, 0.030 ± 0.005; Cd-117, less than 0.01; Sb-127,
> 0.47 ± 0.1; Sb-129, 1.2 ± 0.2; Te-131m, 1.9 ± 0.3;
> Te-132, 4.3 ± 0.6; Ba-139, 6.8 ± 0.4; Ba-140, 6.1 ± 0.6;
> Cs-136, 0.8 ± 0.1. ((The first symbol refers to the
> nuclide. The numbers refer to the fission yield in per
> cent.))

3.7.34 THE COMPLEX ALPHA-SPECTRA OF Am-241 and Cm-242. Frank Asaro, F. L. Reynolds, and I. Perlman (Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California). Physical Review 87, 277-85, July 1952

ABSTRACT

The alpha-particle spectra of Am-241 and Cm-242 was studied in detail utilizing a 75-cm radius of curvature 60° symmetrical electromagnetic analyzer with photographic plate detection. The radioactive sources containing up to 3 ug/cm^2 of active atoms in the case of Am-241 were prepared by vacuum sublimation. The average geometry of the spectrograph is about 4 parts in 10^5. The energy dispersion on the photographic plate is about 3.4 kev/mm for 5-Mev alpha-particles, and the width at half-maximum of these alpha-particle groups is about 7 kev. Six alpha-particle groups were found in Am-241, and their energies and abundances are 5.546 Mev, 0.23 per cent; 5.535, 0.34 per cent; 5.503, 0.21 per cent; 5.476, 84.2 per cent; 5.433, 13.6 per cent; 5.379, 1 42 per cent. In Cm-242 two alpha-particle groups were found whose energies and abundances are 6.110 Mev, 73 per cent, and 6.064, 27 per cent. The alpha-decay scheme is correlated with gamma-rays and conversion electrons observed in this laboratory for both Am-241 and Cm-242. The various alpha-groups are evaluated with respect to the alpha-decay systematics and the degrees of hindrance of the various alpha-transitions are discussed with reference to normal trends in even-even nuclei. It is suggested that the totally different patterns of the spectra of the two nuclides are conditioned by the nuclear types.

((End of Abstract))

((Samples were prepared by vacuum sublimation of curium-chloride from a hot tungsten filament. Average sample sizes were 2 micrograms/cm^2. The complex structure, and the alpha decay theory of Cm-242 are discussed in some detail.))

3.7.35   UCRL-1632. INVESTIGATION OF THE ALPHA PARTICLES OF BISMUTH-203 AND CURIUM-242. Section 13, Nuclear Properties and Transformations. Chemistry Division Quarterly Report, September, October and November 1951. (University of California Radiation Laboratory) page 12, January 28, 1952.

Curium-242. Nuclear emulsions were also used to determine the number of conversion electrons that accompanied the alpha particle emission of Cm-242. It was found that of 4100 alpha particles observed 942 or 23% were accompanied by conversion electrons. Hence, at least 23% of the alpha particle decay of Cm-242 leads to an

excited level of Pu-238. This compares favorably with the presence of a low energy alpha particle group determined by alpha ray spectroscopy to the abundance of approximately 27%. The conversion coefficient of the gamma ray is indicated to be about 100%.

3.7.36   THE L X-RAY SPECTRA FROM RADIOACTIVE DECAY
OF TRANSURANIUM ELEMENTS. G. W. Barton, Jr.,
H. P. Robinson, and I. Perlman (Radiation Laboratory
and Department of Chemistry, University of California,
Berkeley, California). Physical Review 81, 208-13,
1951 ((Also published as AECD-2494))

ABSTRACT

A bent crystal X-ray spectrometer is described and some results are given on the analysis of L series X-rays produced in radioactive decay processes of transuranium elements. There is generally good agreement between measured energy values of L series lines and those predicted by the Mosely relationship. The relative intensities of the various lines produced in this case from gamma ray internal conversion are compared with those from uranium excited by electron bombardment and values reported of internal conversion excited X-rays in the region of lead.

((End of Abstract))

Plutonium X-rays from decay of Curium-242. The isotope Cm-242 is an alpha particle emitter with 162 days half life prepared for the present study by the neutron irradiation of the 475 year Am-241. The alpha decay of Cm-242 includes fine structure in which roughly 20% of disintegrations go to the excited state of Pu-238, about 50 kev above the ground state. The accompanying gamma ray transition is largely internally converted in the L shell and the X-rays measured in the study are those resulting from the refilling of these L orbit vacancies.

3.7.37   NEW ISOTOPES OF BERKELIUM AND CALIFORNIUM.
E. K. Hulet, S. G. Thompson, A. Ghiorso, and K. Street,
Jr. (Radiation Laboratory and Department of Chemistry,
University of California, Berkeley, California). Physical
Review 83, 366-7, July 1951

In the course of work on transplutonium isotopes at Berkeley, it has been possible to prepare mixtures of Am-242, Cm-243, and Cm-244

by intensive neutron irradiation of samples originally consisting of the isotope Am-241. The heaviest curium isotopes are useful sources for the preparation of berkelium and californium isotopes heavier than have been previously observed from helium ion and deuteron bombardments of the isotopes Am-241 and Cm-242. A target containing approximately 100 ug of Cm-242, ∼ 5 ug Cm-243, and ∼2 ug of Cm-244, was bombarded with 35-Mev helium ions and 16-Mev deuterons. The resulting californium and berkelium isotopes were chemically separated from each other, from the target materials, and from fission products using the same combinations of precipitation and ion exchange methods as have been reported previously. The final chemical separations were completed approximately 9 hours after the end of the bombardment.

((The balance of this article is concerned with a discussion of the properties of Bk-243, 246, 247, Cm-243, 245 and Cf-245, 246.))

3.7.38   UCRL-1365. THE DECAY SCHEMES OF PLUTONIUM-239 AND CURIUM-242. Charles Prohaska, Chemistry Division Quarterly Report: March, April, May 1951 (University of California Radiation Laboratory) June 26, 1951

No alpha gamma coincidences are observed. If any gamma rays are in coincidence with alpha particles they are in too low an abundance to be observed with this apparatus. A considerable number of alpha electron coincidences were observed in Cm-242. These may be resolved in two components, 37.5 kev electrons and 25 kev electrons. These correspond to M and L conversion electrons, respectively, of a 43 kev gamma, the abundance of these coincidences is as follows:

> 37.5 kev electrons
> 0.09 coincidences per alpha
> 25 kev electrons
> 0.28 coincidences per alpha

This gives an abundance for the 43 kev transition of 0.37 per alpha and a ratio of L conversion/M conversion = 2.9.

3.7.39   SPONTANEOUS FISSION IN Cm-242. G. C. Hanna, B. G. Harvey, N. Moss and P. R. Tunnicliffe (Atomic Energy Project, National Research Council of Canada, Chalk River, Ontario, Canada). Physical Review 81, 466-7, February 1951.

The spontaneous fission rate was measured as 6.2/minute per 10^6 Cm-242 alpha disintegrations/minute. The over-all limits of error in this figure should not exceed 2%. Using a value of 162.5 days for the alpha half life, the spontaneous fission half life becomes (7.2 ± 0.2) 10^6 years.

3.7.40   MASS SPECTROGRAPHIC IDENTIFICATION OF Cm-242, AND Cm-244. F. L. Reynolds, F. K. Hulet and K. Street, Jr. (Radiation Laboratory, Department of Chemistry, University of California, Berkeley, California) Physical Review 80, 467, November 1950

((This reference deals entirely with the spectrographic lines identification of Cm-242 and Cm-244 and is largely of historical interest.))

3.7.41   THE HALF LIFE OF CURIUM-242. G. C. Hanna, R. G. Harvey and N. Moss (Atomic Energy Project, National Research Council of Canada, Chalk River, Ontario, Canada). Physical Review 78, 617, June 1950

During recent work on the neutron irradiation of americium it was noted that the Cm-242 produced decay at a rate significantly different than that expected from the published half life of 150 days. Accordingly an attempt was made to measure this half life with reasonable precision. Three sources were prepared by evaporation from solution on a mirror finish platinum disc and ignited to red heat. ((As a result of the experiments a best value of 162.7 - 0.2 days or 162.5 days ± 2 days was obtained for the half life of Cm-242.))

3.7.42   THE NEW ELEMENT CURIUM ATOMIC NUMBER 96. G. T. Seaborg, R. A. James and A. Ghiorso, Paper 22.2, The Transuranium Elements Research Papers edited by Glen T. Seaborg, Joseph J. Katz, Winston M. Manning, Part II, Paper 6.40 to 22.80. First Edition, McGraw-Hill Book Co., Inc. 1949

((This article describes the work leading to the discovery of Cm-242 and so is mainly of historical interest.))

3.7.43   UCRL-1243. THE SPECTROMETRIC DETERMINATION OF SOME BETA PARTICLE AND CONVERSION ELECTRON ENERGIES. Grover Davis O'Kelley, A.B., Howard College, 1948. Dissertation. Submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Chemistry in the Graduate Division of the University of California. 1948

Section C, Decay Scheme of Cm-242. The nuclide Cm-242, an alpha particle emitter of 163 days half life, can be prepared in microgram quantities by neutron irradiation of Am-241 and the subsequent decay of Am-242m. Absorption experiments indicated L X-rays and a gamma ray of about 50 kev. No hard electromagnetic radiation is detectable. Internal conversion lines can be assigned to the L, M and perhaps the N conversions of a 43 kev gamma ray.

3.7.44   AECD-2376: NUCLEAR PROPERTIES OF TRANSPLUTO-
          NIUM ISOTOPES. G. T. Seaborg (Argonne National
          Laboratories, Lemont, Illinois) December 1947, 12 p
          (ANL-JJK-14A-161)

Table I. Radioactive properties of transplutonium isotopes. Cm-242; half life 162 ± 3 days, radiation energies, alpha 6.1 Mev (4.75 centimeters). The isotope Cm-242 also emits a small number of 65 kev gamma rays (about 1 per 500 alpha particles) and a small number of conversion electrons and corresponding L X-rays. The isotopic assignment of the radioactivity has been confirmed as the result of the proof that the isotope Pu-238 is its decay product.

3.7.45   ISOLATION OF CURIUM. L. B. Werner and I. Perlman,
          AECD-2148 (BC-74), August 9, 1947, declassified
          September 25, 1947 for oral presentation before the
          meeting of the Chemical Society in New York City
          September 1947

Curium, the fourth of the transuranium elements, has recently been isolated by L. D. Werner and I. Perlman. The isotopes involved use the intensely alpha active isotope Cm-242 of five months half life. The curium was prepared by the irradiation in a high flux pile of a small amount of 500-year Am-241 which had previously been isolated by B. B. Cunningham, L. B. Asprey and A. C. Stewart.

3.8   CURIUM-244

HALF LIFE

(Alpha) 17. 59 ± 0. 06 years   Ref. 3. 8. 11 Journal Inorg. & Nucl. Chem. 17, 12-14, 1961

(S. F.)(1. 46 ± 0. 05)10^7 years   Ref. 3. 8. 5 Atomnaya Energiya 15, 3, 249-59, Sept. 1953

ALPHAS/SPONTANEOUS FISSION

(7. 43 ± 0. 01) 10^5 Private communication with Mr. H. Diamond and Mr. W. C. Bentley, Argonne National Labs. Oct. 1964

NEUTRONS/SPONTANEOUS FISSION

2. 810 ± 0. 059   Ref. 3. 8. 13 Phys. Rev. 101, 1012-15, Feb. 1956

ENERGY LEVELS AND DECAY SCHEME

Cm-244 $\xrightarrow{\text{ALPHA}}$ Pu-240

Alpha Energies (Mev)		Ref. 3. 9. 5 Rev. Mod. Phys. Vol. 30, #2, pt. II, April 1958
	5. 801 (76. 7%)	
	5. 759 (23. 3%)	
	5. 661 (0. 017%)	

Gamma Energies (kev)		Rev. Mod. Phys. Vol. 30, #2, pt. II, April 1958
	43 ($2. 1 \times 10^{-2}$%)	
	100 ($1. 5 \times 10^{-3}$%)	
	150 ($1. 3 \times 10^{-3}$%)	

Ref. 3.9.8.   Rev. Mod. Phys. Vol. 30 #2 pt II, April 1958

3.8.1   SEARCH FOR A SPONTANEOUS FISSION BRANCH IN A
         METASTABLE STATE OF Cm-244.   R. Vandenbosh,
         P. R. Fields, S. E. Vandenbosh and D. Metta (Argonne
         National Laboratory, Argonne, Illinois).   Journal of
         Inorganic and Nuclear Chemistry 26, 219-234, 1964

ABSTRACT

The partial spontaneous fission half life of the 0.034 second (I = 6+)
metastable state of Cm-244 has been found to be greater than, or equal
to, 1.4×10^2 years.   The life time is not reduced as much as one might
expect from the 1.04 Mev excitation energy of the isomeric state.
This hindrance may be due to the intrinsic structure of the metastable
state.

3.8.2   SPECTRUM OF ALPHA PARTICLES IN THE Cm-244
         SPONTANEOUS TERNARY FISSION.   N. A. Perfilov,
         Z. Soloy'eva, and R. A. Filov.   Zh. Eksperim, i. Teor,
         Fiz. 46:2244-5 (June 1964)   (In Russian)

ABSTRACT

The energy spectra of alpha particles in the Cm-244 spontaneous
ternary fission were measured by means of photographic emulsions
and photographic plates.   The energy spectra have a Gaussian
distribution with a maximum at $\sim$ 15.5 Mev.

3.8.3   ISOTOPIC POWER DATA SHEETS.   S. J. Rimshaw (Oak
         Ridge National Laboratory, Oak Ridge, Tennessee).   For
         presentation at Industry Information Meeting on Isotopic
         Power Development and Applications, Washington, D. C.
         May 18-19, 1964

Source Material	Cm_2O_3
Half-Life	18.4 years
Decay and Radiation Properties	Cm-244 $\longrightarrow$ Pu-240 ($T_{1/2}$ = 6.6 x 10^3 years)

Alphas   Gammas
  5.798 Mev (76.7%)   42.9 kev (23.3%)
  5.756 Mev (23.3%)

Spontaneous fission half-life = 1.4×10^7
years

Isotopic Composition	Mixture of Cm-244 and Cm-245
Activity Concentration	72.6 curies per gram of Cm-244$_2$O$_3$
Radiochemical Purity	>99%
Chemical Purity	~95% with ~5% Am-243 (product specifications not established)
Specific Power	2.5 watts per gram of curium oxide or 34.28 watts/kilocurie
Thermal Energy	29.2 curies per thermal watt
Density	Theoretical density is 11.2 g/cm^3. Practical density is ~9.0 g/cm^3 (~80% of theoretical density)
Power Density	22.5 watts/cm^3 for Cm-244$_2$O$_3$ with a density of 9.0 g/cm^3. About 0.5% of the total power will be contributed by the 5% Am-243
Thermal Conductivity	0.028 watts/cm °C at 125°C (based on Gd$_2$O$_3$)
Coefficient of Expansion	10.5 x 10^{-6}/°C (25° to 1000°C) (based on Gd$_2$O$_3$)
Melting Point	1950°C in helium
Mechanical Properties	Modulus of elasticity (sonic) 14.5 x 10^6 lb/in^2 at 25°C (based on Gd$_2$O$_3$)
Thermal and Radiation Stability	No data available
Radiation Attenuation	Neutron shielding is required. See Shielding Handbook by E. D. Arwold, ORNL-3576 for shielding requirements, and also ORNL-TM-591 (rev.)

Gas Evolution Due to Radioactive Decay Processes	Helium accumulates as a result of alpha decay. An original 1000-curie source of Cm-244 will produce 85.2 cm^3 of helium in two years (0.11 half-lives)
Leach Rate	No data available
Vapor Pressure	No data available
Resistance to Thermal Shock	No data available
Burnup Characteristics	Dispersibility poor
Capsule Compatibility	No data available

3.8.4   REFER TO 3.6.3.   ALPHA SOURCES FOR LOW THRUST TASKS IN SPACE.   International Journal of Applied Radiation and Isotopes.   15, 127-31, March 1964

3.8.5   THE ENERGY DISTRIBUTION OF Cm-244 SPONTANEOUS FISSION FRAGMENTS.   L. Z. Malkin, I. D. Alkhazov, A. S. Krivokltatskii, K. A. Petrzhak and L. M. Belov, Atomnaya Energiya 15, 3, 249-259, September 1963 (Translated in Atomic Energy USSR 15, 249-50, 1963)

The working specimen spread on a platinum substrate contained 0.243 micrograms of Cm-244, 0.0059 micrograms of Cm-242 and not more than 0.046 micrograms of Pu-238.   When the energy distribution of the Cm-244 spontaneous fission fragments was plotted the contribution from spontaneous fission of Pu-238 was found to be negligible and was left out of the consideration but a correction was made for the contribution from the spontaneous fission of Cm-242.   The spontaneous fission period for Cm-242 was assumed to be 7.2×10^6 years.   ((On the basis of the experiment described in this article the spontaneous fission period was found to be $(1.46 \pm 0.05) \times 10^7$ years.))

3.8.6   DECAY OF AN ISOMERIC STATE IN Cm-244.   P. G. Hansen and K. Wilsky, Chemistry Department (Research Establishment) Riso, Denmark, Nuclear Physics 45, 410-416, 1963

ABSTRACT

The 1042 kev state of Cm-244 which is postulated in the beta decay of
10. 1 hour Am-244 has previously been assigned (k, 1π) = (6, 6+).
This assignment has now been confirmed through an angular correlation
measurement and it was found that the 746 kev gamma ray is a mixture
of 46% quadrupole (E2) and 54% dipole (M1). The half life of the 1042
kev state has been determined by the measurement of delayed coinci-
dences between beta particles and conversion electrons. The result
is 34 ± 2 ms. Comparison with the single particle estimate shows
that the E2 transitions from the delayed state are hindered by factors
of about 10^{10}. This reflects the fact that the transitions are 4 times
forbidden in K. The relative transition probabilities for the E2's
from the delayed state are shown to agree well with a recent theoretical
estimate.

3. 8. 7   REFER TO 3. 7. 2. ALPHA DECAY OF CURIUM ISOTOPES.
           J. Exptl. Phys. USSR 45, 1360-71. Nov. 1963.

3. 8. 8   LIFETIME OF THE FIRST TWO PLUS LEVEL IN Cm-244.
           Rex Christensen (Institute for Theoretical Physics,
           University of Copenhagen, Denmark). Nuclear Physics
           37, 482-485, 1962

ABSTRACT

The half life of the 42. 9 kev 2+ level in Cm-244 has been measured
using the delayed coincidence method. The exponential decay was
directly observed in the time spectra. The result obtained in half
life equals (0. 97 ± 0. 05) x 10^{-10} seconds.

3. 8. 9   REFER TO 3. 7. 4. ENERGY OF ALPHA PARTICLES
           FROM SOME CURIUM ISOTOPES. Izvestia Akad Nauk,
           USSR 26, 976-8, Aug. 1962

3. 8. 10   REFER TO 3. 7. 5. Cm-216 LONG RANGE PARTICLES
           FROM NUCLEAR FISSION. Phys. Rev. 116, 1508-1513,
           May 1962

3. 8. 11   THE ALPHA HALF LIVES OF Cm-244, Cm-245, and
           Cm-246. W. T. Carnall, S. Fried, and A. L. Harkness,
           (Argonne National Laboratory, Argonne, Illinois).
           Journal of Inorganic and Nuclear Chemistry 17, 12-14,
           1961

ABSTRACT

The alpha half life of Cm-244 determined from specific activity measurement and the alpha half lives of Cm-245 and 246 determined by mass spectrometric analysis of curium and its plutonium daughters have been determined to be 17.59 ± 0.06 years, 9320 ± 280 years and 5480 ± 170 years, respectively.

3.8.12   REFER TO 3.5.23. ABSOLUTE ENERGY MEASURE-MENT OF ALPHA PARTICLES FROM Po-210. Phys. Rev. 109, 437-442, Jan. 1958.

3.8.13   UCRL-3456. ALPHA DECAY STUDIES IN THE HEAVY ELEMENT REGION. John Phillip Hummel (University of California, Radiation Laboratories, Berkeley, California) July 3, 1956

Section C. Alpha Decay of Cm-244. (See Figure Cm4-1 and reference 3.7.17.))

3.8.14   MULTIPLICITIES OF FISSION NEUTRONS. B. C. Diven, H. C. Martin, R. F. Taschek and J. Terrell (Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico). Physical Review 101, 1012-15, February 1956

((The following is a representation of the abstract as it pertains to Cm-244. Several other fissionable isotopes are described in this article.))

A large liquid scintillator with approximately 80% efficiency for detection of neutrons has been used to obtain data on numbers of neutrons emitted per fission for several fissioning nuclides. Reported here are the average number of neutrons per fission and the respective probabilities of 0, 1, 2... neutrons per fission for spontaneous fission of Cm-244 (and several other isotopes). The value for Cm-244 is 2.810 ± 0.059 neutrons per spontaneous fission. The probabilities of 0, 1, 2 ... neutrons per fission approach closely a binomial distri-bution with a maximum number of neutrons equal to 5, 6, or 7, depending upon $\bar{\nu}$. ((Table 2 contained in this article presents a summary of the results of the experiments on all of the fissionable materials studied. This table is not reproduced here.))
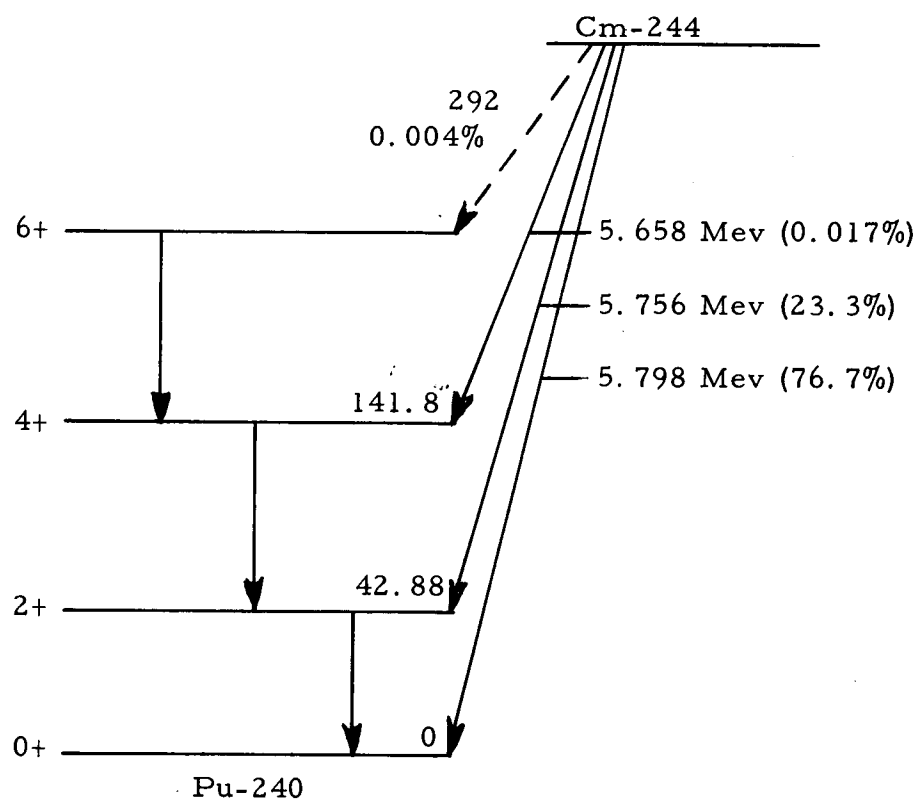
FIGURE Cm4-1.   DECAY SCHEME FOR Cm-244

3.8.15   REFER TO 3.6.19.   PROBABILITIES OF PROMPT
         NEUTRON EMISSION FROM SPONTANEOUS FISSION.
         Phys. Rev. 101, 746-50, Jan. 1956

3.8.16   AVERAGE NUMBER OF NEUTRONS PER SPONTANEOUS
         FISSION OF Cm-244.   J. M. Higgins, W. W. T. Crane,
         and S. R. Gunn (Radiation Laboratory, Livermore,
         California).   Physical Review 99, 183, July 1955

ABSTRACT

The average number of neutrons per fission for Cm-244 had been
measured by the manganous sulphate moderator absorber system.
The value 2.60 ± 0.11 has been determined.   A sample of Cm-244
was purified by ion exchange techniques and electroplated on a
platinum foil of about 20 square centimeters area.   The foil was
rolled tightly and the heat from it was measured calorimetrically.
The calorimeter used was of the steady state resistance bridge type
used at the Mound Laboratory.   The accuracy of the present
measurement was to within about 1%.

3.8.18   REFER TO 3.7.20.   CONVERSION ELECTRON SPECTRA
         OF Cm-242 AND Cm-244.   Phys. Rev. 99, 47-55, July
         1955

3.8.19   UCRL-2932.   DECAY CHARACTERISTICS OF SOME
         HEAVY ISOTOPES.   (University of California Radiation
         Laboratory Chemistry Division Quarterly Report
         December 1954 - January, February 1955).   Isador
         Perlman, Frank Asaro, Frank S. Stephens, John P.
         Hummel, and Richard C. Pilger.

Curium-244.   The abundances of $alpha_0$ and $alpha_{43}$ in Cm-244 decay
were measured with an alpha particle spectrograph as 76.7 and 28.3,
respectively.   Their gamma energy separation was 43.0 kev.   A new
alpha group 142.7 kev lower in decay than the main group was found in
an abundance of 0.014%.   The ratio of the energies of the second
excited state to the first excited state was 3.32 from the Bohr
Mottelson theory.   The 43- and 143-kev states have spins of 2+ and 4+.
The conversion coefficient of the 43 kev gamma ray was measured and
indicated the spin of 43 kev state was 2+.

3.8.20   REFER TO 3.6.23.   NUCLEAR PROPERTIES OF THE
           PLUTONIUM ISOTOPES.   McGraw-Hill Publishing Co.
           1954

3.8.21   REFER TO 3.6.24.   CORRELATION OF SPONTANEOUS
           FISSION HALF LIVES. Phys. Rev. 96, 545-6, October
           1954

3.8.22   ALPHA HALF LIVES OF Cm-244, Cm-245, AND Cm-246.
           A. M. Friedman, A. L. Harkness, P. R. Fields, M. A.
           Studier and J. R. Huizenga, Physical Review 95, 1501,
           September 1954

ABSTRACT

The alpha half lives of Cm-244, Cm-245, and Cm-246 measured from
mass spectrometric analysis of curium and its plutonium daughters
are 18.4 ± 0.5 years (weighted average of present results and those
reported in reference 1)**, (1.15 ± 0.5) 10^4 years and (4.0 ± 0.6) 10^3
years, respectively.

((End of Abstract))

The alpha half lives of Cm-244, 245, and 246 have been determined by
a technique which depends upon the growth of the plutonium daughters
from a curium sample of known isotopic composition.

**Reference 1 is Physical Review 94, 1083, 1954

3.8.23   CURIUM ISOTOPES 246 and 247 FROM PILE-IRRADIATED
           PLUTONIUM.   C. M. Stevens, M. H. Studier, P. R.
           Fields, P. A. Sellers, A. M. Friedman, H. Diamond and
           J. R. Huizenga (Argonne National Laboratory, Lemont,
           Illinois).   Physical Review 94, 974, May 1954

ABSTRACT

Mass spectrometric analyses show the presence of Cm-246 and Cm-247
in curium samples produced from neutron-irradiated plutonium. The
pile-neutron capture cross sections of Am-243, Cm-244, Cm-245, and
Cm-246 are 115 ± 20, 25 ± 10, 200 ± 100, 15 ± 10 barns, respectively.
The alpha-disintegration half-life of Cm-244 is calculated to be $19.2 \pm$
0.6 years.

((End of Abstract))

The curium produced by the irradiation of two plutonium samples (total integrated fluxes 4×10^{21} and 8×10^{21} neutrons) in the Materials Testing Reactor (MTR) was chemically purified from fission products and other actinide elements. The plutonium was removed by utilizing its multivalent character. The transplutonium elements were freed of fission products by standard cation resin column techniques. Finally, the curium was separated from americium and the transcurium elements by an ion-exchange column of Dowex 50 resin in the ammonium form eluted with 0.25M citrate solution at a pH of 3.3 at 98°C. The column was 20 cm long with a cross-sectional area of 0.1 square cm. The actinide elements elute at different rates and the various fractions were collected and repurified.

3.8.24   REFER TO 3.7.28. THE ALPHA SPECTRA OF Cm-242, Cm-243, Cm-244. Phys. Rev. 92, 694-702, Nov. 1953.

3.8.25   SPONTANEOUS FISSION OF U-234, Pu-236, Cm-240, and Cm-244. A. Ghiorso, G. H. Higgins, A. E. Larsh, G. T. Seaborg, and S. A. Thompson, (Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California). Physical Review 87, 163-4, 1952. ((Identical to UCRL-1777.))

((This article consists of an experimental re-determination of the fission half lives of the four isotopes mentioned in the title of this article. The information presented for Cm-244 in the article is as follows: fissions per gram hour $(1.4 \pm 0.2)\ 10^{10}$; half life in years is $(1.4 \pm 0.2)\ 10^{7}$.))

3.8.26   UCRL-1772. SPONTANEOUS FISSION OF URANIUM-234, PLUTONIUM-236, CURIUM-240, AND CURIUM-244. A. Ghiorso, G. H. Higgins, A. E. Larsh, G. T. Seaborg, and S. G. Thompson (University of California Radiation Laboratory). April 21, 1952

Spontaneous fission rates were measured by placing the chemically purified samples on one electrode of a parallel plate ionization chamber filled with a mixture of argon and carbon dioxide which was connected with an amplifier followed by a register and a stylus recorder. The results are summarized (as follows): Spontaneous fission rates of Cm-240, and Cm-244; Cm-240 fissions per gram hour, $1.0 \pm 0.2 \times 10^{11}$, spontaneous fission half life in years, $1.9 \pm$

0.4 x 10^6; Cm-244 fissions per gram hour 1.4 $\pm$ 0.2 x 10^{10}, spontaneous fission half life in years, 1.4 $\pm$ 0.2 x 10^7.

3.8.27   UCRL-1365.   SPONTANEOUS FISSION OF CURIUM-244.
A. E. Larsh, A. Ghiorso, and S. C. Thompson,
Quarterly Progress Report Project 48.   Nuclear
Properties and Transformations.   Chemistry Division
Quarterly Report: March, April, May, 1951.   (University
of California Radiation Laboratory).   Pages 9 and 10,
June 26, 1951

The heaviest isotope of Cm-244 has been shown to undergo spontaneous fission with the extremely high ratio of 1.3 $\pm$ 0.2 spontaneous fission per 10^6 alpha disintegrations.   This value is about twenty times higher per alpha disintegrations than that for Cm-242 known from early work to be 0.062 spontaneous fissions per 10^6 alpha disintegrations.   The measurements were made on almost pure Cm-244 produced in the Handford pile by neutron bombardment of Pu-242 through the reaction Pu-242 (n, gamma) Pu-243 $\longrightarrow$ Am-243 (n, gamma) Am-244 $\longrightarrow$ Cm-244.   A small amount of Cm-242 by weight was present in the sample, having been formed by other neutron reactions, but its contribution to the spontaneous fission rate was only about twenty per cent.   Assuming a half-life of some forty years as discussed in other sections of this report the half-life of spontaneous fission of Cm-244 is approximately 3 x 10^7 years.

3.9   ADDITIONAL SOURCES OF INFORMATION

3.9.1   QUARTERLY PROGRESS REPORT, RADIOISOTOPE
EVALUATION PROGRAM.   V. Truscello, M. Kniedler,
T. Bustard (Nuclear Division, Martin Company, Baltimore,
Maryland).   Report #MNSP-VT-4017.   15 September 1964

This report presents the results of the first three months of a six
month study-experimental effort to investigate and evaluate several
isotopes as heat sources for scientific satellite power supplies.
Isotopes reviewed are Sr-90, Pu-238, Cm-244, Cm-242, Po-210,
Ce-144, Pm-147, Cs-134, and Cs-137.   Characteristics studied are
nuclear and chemical properties, thermal and physical properties,
and production and availability.

Experimentation to measure the external bremsstrahlung of Pm-147 in
various materials also is described.

3.9.2   (TID-3561 (Rev. 4)).   SYSTEMS FOR NUCLEAR AUXILIARY
POWER (SNAP).   A literature search, Henry D. Raleigh,
comp. (Division of Technical Information Extension, AEC)
June 1964. 80 p.

A bibliography of 324 references to publications on the SNAP program
and related nuclear-powered generators is presented.   The references
cover the period January 1956 through April 15, 1964.   Author and
report number indexes are included.

3.9.3   ORNL-3576 (TID-4500).   HANDBOOK OF SHIELDING
REQUIREMENTS AND RADIATION CHARACTERISTICS
OF ISOTOPIC POWER SOURCES FOR TERRESTRIAL,
MARINE, AND SPACE APPLICATIONS.   E. D. Arnold
(Oak Ridge National Laboratories, Oak Ridge, Tennessee)
April 1964

Isotopic power or radiation sources for use in terrestrial, marine,
and space applications require shielding or a degree of isolation to
prevent excessive radiation doses to personnel handling the source, to
prevent excessive radiation damage to instrument systems associated
with the mission or application, and to prevent interference with
experimental measurements that use radiation detection instruments.
This report is in essence a handbook of radiation properties and
shielding requirements for isotopic power or radiation sources and is
intended primarily for use in preparation of preliminary design
estimates by design engineers in the field of isotopic source develop-

ment and application. The calculated radiation intensities are probably slightly pessimistic in that they are over-estimated no more than 50%. It therefore may be necessary to optimize the shield for an actual source from experimental data on the source itself. Actual measurements, proving the integrity of a shield, are necessary for licensing by the federal government. Calculations have been made of the radiation intensities from shielded and unshielded sources fabricated from seventeen isotopes that show promise for use in isotopic power or radiation applications. Source sizes in the range of 100 to 20,000 thermal watts were evaluated. All shielded sources were assumed to be attenuated by iron, lead, and uranium; and in those cases where the source also emitted neutrons, neutron and gamma attenuation through water was determined.

The isotopes studied and their physical form are as follows: Co-60 (metal), Kr-85 (liquefied gas), Sr-90 (oxide and titanate), Zr-Nb-95 (oxide), Ru-106 (metal), Cs-137 (glass), Ce-144 (oxide), Tm-170 and Tm-171 (both as oxides), Tl-204 (metal), Po-210 (metal matrix with void space for gas collection), U-232 (oxide), Th-228 (oxide matrix with void space for gas collection), and Pu-238 (oxide), Cm-242 (oxide matrix with void space for gas collection), and Cm-244 (oxide).

For the reader's convenience, several samples of how the graphical results may be used to calculate separation distance, shield thickness, and shield weight are included.

3.9.4   *(AED-C-15-02). AUSGEWAHLTES SCHRIFTTUM NACH SACHGEBIETEN. KERNABATTERIEN. BIBLIOGRA-PHISCHE ZUSAMMENSTELLUNG. (Selected literature according to subject field. Nuclear Batteries. Bibliographic Compilation). (Battelle Institute, V., Frankfurtam Main). Sept. 1963. 127 p. (In German)

Five hundred and thirty references, covering the period 1959 to 1963, on nuclear batteries are presented. Report number, author, and subject indexes are included.

3.9.5   TID-3561 (rev. 3). DIRECT ENERGY CONVERSION AND SYSTEMS FOR NUCLEAR AUXILIARY POWER (SNAP) A LITERATURE SEARCH. Sidney F. Lanier, Henry D. Raleigh, January 1963.

((This document gives references on many aspects of the SNAP program. These are (1) Radioisotope fueled units. (2) Reactor

fueled units. (3) Direct energy conversion. (4) General topics on nuclear auxiliary power. For the most part, those references dealing directly with the nuclear characteristics of the various isotopes are contained elsewhere in the bibliography.))

3. 9. 6   MND-P-2581-1.   ISOTOPIC POWER SOURCES, PROPERTIES, AND PROCESSES REVIEW.   A COMPEN-DIUM.   E. H. Smith, William Bowes (The Martin Company, Baltimore, Maryland)   June 1961

A selective bibliography has been compiled containing 2063 references to reports and published literature on isotopes usable as power sources. The source was NUCLEAR SCIENCE ABSTRACT, Volumes 1 through 14 (1948 to 1960).   Nuclear, physical and chemical properties and separation processes have been emphasized; biological aspects have been excluded.   The isotopes covered are Sr-90, Cs-137, Ce-144, Pm-147, Po-210, Ra-228, Ac-227, Th-228, U-232, Np-237, Pu-238, Pu-239, Pu-241, Am-241, Cm-242, Cm-243, and Cm-244.   The thoroughness of the search was greatest for the transuranium isotopes, Pm-147, Po-210 and Ac-227 but was deliberately restricted to the most pertinent information about U-232, Th-228 and the fission product elements.   The bibliography is arranged according to elements, modified by the number of references included.

((The unrestricted portion of this report is in three volumes.   The first volume consists of reference titles and sources only.   Volume two (entitled part I) covers the fission products and isotopes with (72- $<$ Z$<$ -93) and goes into detail concerning the properties described above.   Volume three (entitled part II) is devoted to plutonium and the transplutonium elements and goes into the same detail as volume two. The restricted portion of this report was published as MND-P-2581-II.))

3. 9. 7   DECAY SCHEMES OF RADIOACTIVE NUCLEI. Dzhelepov and P. Eker, Pergamon Press, 1961

3. 9. 8   TABLE OF ISOTOPES.   D. Strominger, J. M. Hollander, G. T. Seaborg (Department of Chemistry and Radiation Laboratory, University of California, Berkeley, California) Reviews of Modern Physics, Vol. 30, Number 2, part II 585-904, April 1958

((This document contains a listing of all of the radioactive and stable isotopes of the elements, together with a number of their salient

features, as recorded in the literature or by private communication to February 1958. Included in the description of each isotope is the following information:

1. Half life
2. Type of decay (including spontaneous fissions)
3. Class and identification
4. Per cent abundance
5. Nuclear moments
6. Energy of radiation
7. Disintegration energy and scheme

The value of this document to the researcher cannot be over-stated.

Although many of the references contained in the Table of Isotopes are also contained in this bibliography, the possession of a copy of the Table of Isotopes by the researcher is almost mandatory. ((Editions of the Table of Isotopes also appeared in:

1. Reviews of Modern Physics 25, 469, 1953
2. Reviews of Modern Physics 20, 585, 1948
3. Reviews of Modern Physics 16, 1, 1944
4. Reviews of Modern Physics 12, 30, 1940

Because the Table of Isotopes appears as an accumulative document, these earlier editions are mentioned only for the sake of completeness.))

3.9.9   NATIONAL NUCLEAR ENERGY SERIES. Division IV,
          Vol. 9 - 14 b. McGraw-Hill Book Company 1949

((This series comprises what is probably the most thorough compilation of the Manhattan Project literature on the fission products and the plutonium and transplutonium isotopes. However, much of the information contained in these volumes is now mostly of historical interest.))

3.10 MISCELLANEOUS REFERENCES

3. 10. 1 RADIOISOTOPIC SPACE POWER-PROSPECTS AND LIMITATIONS.   C. A. Rohrmann and E. D. Sayre (General Electric Company, Richland, Washington). New York, American Institute of Aeronautics and Astronautics, 1964. Paper No. 64-453, 9 p. $1.00. (CONF-600-28)

From American Institute of Aeronautics and Astronautics 1st Annual Meeting, Washington, D. C., June-July 1964. The properties of Co-60, Sr-90, Cs-137, Ce-144, Pm-147, Tm-170, T1-204, Po-210, Th-228, U-232, Pu-238, Am-241, Cm-242 and Cm-244 are reviewed for use in radioisotope heat sources for direct conversion devices.

3. 10. 2 HW-78658.   ISOTOPIC SEPARATION AS A FACTOR IN THE SELECTION OF CANDIDATE HEAT SOURCE RADIOISOTOPE.   Charles A. Rohrmann (General Electric Company, Standford Atomic Products Operations, Richland, Washington).   September 3,1963

((This document presents no original information on the nuclear characteristics of radioisotopes.))

3. 10. 3 WASH-1044 REPORTS TO THE AEC NUCLEAR CROSS-SECTION ADVISORY GROUP.   Meeting at the University of Colorado, August 13, 14, 1963

((Document is concerned mainly with nuclear cross-sections. However, no significant information is presented for the isotopes under study.))

3. 10. 4 NYO-10689.   A BIBLIOGRAPHY ON RADIOISOTOPE POWER SUPPLIES.   Daniel M. Axlerod and Joseph P. Novarro, August 1963. 30 pages

((This article is mainly concerned with the economic aspects of isotope power supplies and the packaging of them.))

3. 10. 5 NP-11455.   DIRECT ENERGY CONVERSION LITERATURE ABSTRACTS.   Compiled in the Library Branch Technical Information Division, April 1962. U. S. Naval Research Laboratory, Washington 25, D. C.

((This document contains no direct references concerning the nuclear properties of the isotopes of interest. It is mainly concerned with mechanical assemblies, chemical separation processes, physical preparation processes, and so on.))

3.10.6   TID-16939. RELATIVE CROSS-SECTIONS FOR FORMATION FOR THE SHIELDED ISOMERIC CESIUM-134m AND CESIUM-134 IN MEDIUM ENERGY FISSION. R. Vandenbosch and H. Warhanek (Argonne National Laboratories, Argonne, Illinois). July 1962, 18 p.

((This article is concerned entirely with nuclear cross-sections.))

3.10.7   ARF-1122-27. ISOTOPIC SOURCES OF SECONDARY RADIATION. I. Filosofo. Feb. 1961, 131 p.

((This article is primarily concerned with mechanical assemblies using isotopes, and so is not of primary importance to this program.))

3.10.8   WASH-1029, UC-34 REPORTS TO THE AEC NUCLEAR CROSS-SECTIONS ADVISORY GROUP; ARGONNE NATIONAL LABORATORY. Physics and Mathematics. September 19-21, 1960.

((There is no significant information in this article. Article is concerned mainly with nuclear cross-sections.))

3.10.9   MND-P-2374. 13 WATT CURIUM FUELED THERMO-ELECTRIC GENERATOR FOR HARD LUNAR IMPACT MISSION. Final Report sub task 5.8 by J. Bloom. (Physics and Mathematics, Martin Company, Baltimore, Maryland) August 1960

3.10.10   IDO-17648 MTR-ETR. TECHNICAL BRANCHES QUARTERLY REPORT. April 1 - June 30, 1960

((This article is concerned for the most part with activation cross-section analysis and is not directly concerned with the physical properties or the half life of isotopes.))

3.10.11   IDO-16648 MTR-ETR. TECHNICAL BRANCHES QUARTERLY REPORT. April 1 - June 3, 1960. Phillips Petroleum Company, Atomic Energy Division National Reactor Testing Station, U.S. Atomic Energy Commission.

((This article is concerned in part with the half life of Cesium-134m, and with activation cross-sections for Pm-147.))

3. 10. 12   TID-3540.   ISOTOPIC POWER AND THERMIONIC CONVERSION.   A LITERATURE SEARCH.   Raymond L. Scott, comp. Dec. 1959, 12 p.

((All applicable references contained in this document are described elsewhere in the subject report.))

3. 10. 13   MND-LIB-1631.   THERMOELECTRIC POWER SOURCES. AN ANNOTATED LITERATURE RESEARCH PART I. George E. Halpern and Elizabeth G. Sanford, Dec. 5, 1958.   24 p.

((All applicable references contained in this document are contained elsewhere in the subject report.))

3. 10. 14   KAPL-1660.   AEC RESEARCH AND DEVELOPMENT REPORT.   Physics and Mathematics, M-3679, 18th edition.   Knolls Atomic Laboratory, New York.   Physics Report of the Research Operation, September, October, November 1956.

((The isotopes reference in this document is to Cm-244.   However, this isotope was used only as a standardizing isotope for a mass spectrometer that was being calibrated.))

3. 10. 15   NYO-3298.   ALPHA GAMMA COINCIDENCES AND ANGULAR CORRELATION IN POLONIUM-210.   G. H. Minton, Feb. 20, 1952, 50 p.

((This article contains no original information on the nuclear characteristics of polonium as needed for the project.))

4.0   THE LOW ENERGY BREMSSTRAHLUNG COMPUTER PROGRAM

4.1   DESCRIPTION OF THE BASIS OF THE BREMSSTRAHLUNG CALCULATION

4.1.1   INTRODUCTION

The calculation of the external radiation arising from the mechanism of bremsstrahlung within a radioisotopic heat source begins with computing the beta ray spectrum of the radioisotope. After the beta ray spectrum has been obtained, the bremsstrahlung spectrum arising from each element of the beta ray spectrum must be computed. The bremsstrahlung spectrum of the fuel element is therefore a summation of many spectra, some of which have high energy end points, others which have low energy end points, and still others that have end points that lie between.

In order that the calculation could be placed in a tractable form, certain assumptions were necessary. Among the assumptions that have been made are the following:

(1)   All of the beta rays of Pm-147 interact with the Pm_2O_3 in accordance with the probabilities expressed in the bremsstrahlung cross sections, i.e., no beta rays escape from the fuel element without the bremsstrahlung interaction probabilities governing the process.

(2)   All bremsstrahlung radiations >10 kev escape from the fuel element, f (ux) = 1.

(3)   No bremsstrahlung radiations <10 kev escape from the fuel element.

(4)   Characteristic X-rays of the chemical elements in the fuel element are ignored.

(5)   Secondary interactions of all types have been neglected in the formal mathematical description of the processes.

(6)   Secondary interactions have been crudely included in the choice for the range of beta-ray interactions.

Given the opportunity for more detailed analysis, one or more of the above assumptions could be eliminated through an extension of the mathematical descriptions of the processes.

4.1.2 THE BETA-RAY SPECTRUM OF Pm-147

Langer, Motz, and Price (1) have indicated that the beta-ray spectrum of Pm-147 produces a Fermi plot of allowed shape, but that the ft value* suggests transitions that are of the first forbidden type. The beta spectrum function may then be taken to be as follows:

$$\text{Beta spectrum function} = f(Z, p) \ W(W_o - W)^2 \ \triangle W/p \qquad (1)$$

where:

$f(Z, p)$ = Fermi function for allowed transitions

p = momentum of emitted beta particle in mc units

W = total energy of the emitted beta particle in mc^2 units

W_o = maximum total energy of the transition in mc^2 units

Of course, the total energy of the electron is the sum of the rest energy of the mass of the electron and the kinetic energy at which it is emitted.

The Fermi function for allowed transitions was taken from the work of Feister (2) and Hall (3). The work of Hall was found to be in error as it was published. However, in examining the series approximation to the complex gamma function the correct form of the approximation to the Fermi function was obtained. Good agreement with the values published by Feister was obtained from the approximation outlined by Hall after the correct form of the equation was determined. The approximation of the Fermi function used on this project is given as Equation (a) in the Table of Equations, Table 4.I. An important relationship is also shown as Equation (b) in the Table.

When the definition of the curie is taken into account, the number of electrons per unit energy interval that is to be the basis of the bremsstrahlung calculation is described by the equation:

*Comparative half-period, Evans (11)

TABLE 4. I

TABLE OF EQUATIONS

$$f(Z, p) = 2\pi\, p_o^{2x}\,\left(1 + \frac{A^2}{p_o^2}\right)^{x-0.5}\left(1 + \frac{x}{6\left(1 + \frac{A^2}{p_o^2}\right)}\right)\exp\left(2x + 2y\,\arctan\frac{x}{y}\right)$$

(a)

$$F(Z_e, W) = f(Z, p)/p^2$$

(b)

$$d\sigma = Z^2 R_o^2\,\alpha\,\frac{16}{3K}\,\frac{1}{p_o^2}\,\ln\left(\frac{p_o + p}{p_o - p}\right)dK, \quad 0.01 < K < 0.1 \text{ Mev}$$

(c)

$$d\sigma = Z^2 R_o^2\,\alpha\,\frac{p}{Kp_o}\left\{\frac{4}{3} - 2E_o E\left(\frac{p^2 + p_o^2}{p^2 - p_o^2}\right) + \frac{\epsilon_o E}{p_o^3} + \frac{\epsilon E_o}{p^3}\right.$$

$$- \frac{\epsilon\epsilon_o}{p_o p} + L\left[\frac{8 E_o E}{3 p_o p} + \frac{K^2 (E_o^2 E^2 + p_o^2 p^2)}{p_o^3 p^3} + \frac{K}{2 p_o p}\right.$$

$$\left.\left\langle \left(\frac{E_o E + p_o^2}{p^3}\right)_o - \left(\frac{E_o E + p^2}{p^3}\right) + \frac{2K E_o E}{p^2 p_o^2}\right\rangle\right]\right\}, \quad 0.1$$

$$< K < 2.0 \text{ Mev}$$

(d)

$$d\sigma_c = d\sigma\, E_f \qquad 0.01 < K < 0.1 \text{ Mev}$$

(e)

$$d\sigma_c = d\sigma\, E_f A \qquad 0.1 < K < 2.0 \text{ Mev}$$

(f)

$$E_f = \frac{\beta_o\,(1 - \epsilon^{-2\pi\alpha\, Z/\beta_o})}{\beta\,(1 - \epsilon^{-2\pi\alpha\, Z/\beta})}$$

(g)

$$A = 1.134\,(1.667)^{T_o} \qquad T_o > 0.1 \text{ Mev} \quad \text{Promethium}$$

(h)

$$A = 0.9858\,(1.564)^{T_o} \qquad T_o > 0.1 \text{ Mev} \quad \text{Oxygen}$$

(i)

$$L = 2\ln\left(\frac{E_o E + p_o p - 1}{K}\right); \quad \epsilon_o = \ln\left(\frac{E_o + p_o}{E_o - p_o}\right)$$

$$; \quad \epsilon = \ln\left(\frac{E + p}{E - p}\right)$$

(j)

$$\overline{DBE(I)} = 3.253(10)^{11} f(Z, p) \frac{W}{p} (W_o - W)^2 \triangle W, \qquad (2)$$

an equation that appears in the listing of the main computer program. The integral of this expression is the definition of the curie, $3.7(10)^{10}$ disintegrations/sec.

4.1.3 CALCULATION OF THE BREMSSTRAHLUNG DIFFERENTIAL CROSS SECTIONS

The calculation of the beta ray bremsstrahlung spectrum of Pm-147 requires for each energy increment of electrons in the beta ray spectrum that a set of bremsstrahlung differential cross sections be computed. In this portion of the computation, the work of Koch and Motz (4) was the most significant in delineating the equations that made a comparatively simple engineering task out of a very difficult derivation in theoretical physics. As outlined by Koch and Motz, there are two energy ranges of interest to the program at hand. One of these extends from 0.01 Mev to 0.1 Mev, and the second extends from 0.1 Mev to 2.0 Mev.

Equations (c) and (d) of the Table of Equations set forth the differential cross sections for the production of bremsstrahlung in the energy range from 0.01 Mev to 2.0 Mev. It should be noted that these equations are not exact. They have been derived with the Born approximation, a condition in which $2 \pi Z \alpha / \beta \ll 1$ and $2 \pi Z \alpha / \beta_o \ll 1$. In the lower range of energies that is of interest here, the cross sections are too small. The corrected cross sections are given in Equations (e) and (f). The Elwert factor E_f is defined in Equation (g). The correction factor, A, is defined for promethium and oxygen in Equations (h) and (i), respectively. Other coefficients that are a part of Equation (c) are defined in a group of three Equations (j).

The equations defining the correction factor A in the Table of Equations were derived from the work of Koch and Motz (4). Specifically, graphical data of Fig. 23 of the referenced article (page 948) were derived from promethium and oxygen. The equations for A as quoted in the table were derived from the least squares fit of an equation of the general form $C(B)^x$.

4.1.4 CALCULATION OF THE BETA RAY BREMSSTRAHLUNG SPECTRUM OF A COMPOUND

The calculation of the beta ray bremsstrahlung spectrum of a compound was planned to be performed in two steps. The first

step was the calculation of the bremsstrahlung spectral elements for the chemical element promethium. The second step was the computation of the bremsstrahlung spectral elements for the chemical element oxygen. Investigation showed that interaction probabilities were very small. As a consequence of this observation it was decided to approach the computation on a linear basis. Briefly stated, where the probability for an interaction is given by

$$P = 1 - \epsilon^{-ux}, \tag{3}$$

the approximation

$$P = ux \tag{4}$$

may be used for values of $ux \ll 1$. This is the thin target type of bremsstrahlung calculation.

Since the bremsstrahlung cross sections are computed as a quantity per atom, the number of atoms to be considered as potential participants must be determined. Of course, it is known that low energy electrons have a short range and hence would have a limited number of interaction possibilities. On the other hand, the more energetic electrons will have a greater range and a corresponding larger number of interaction possibilities. Flammersfeld's equation for beta ray range was selected to define a quantity proportional to this relationship. Flammersfeld's equation follows:

$$R = 0.11 \left(\sqrt{1.0 + 22.4E_b^2} - 1.0 \right). \tag{5}$$

In the above expression

$$R = \text{range of electrons in material, gm/cm}^2$$

$$E_b = \text{energy of electrons, Mev.}$$

An elementary calculation discloses that the compound Pm_2O_3 is composed of $1.762(10)^{21}$ molecules Pm_2O_3 per gram. Furthermore, there are $3.524(10)^{21}$ atoms Pm/gm Pm_2O_3 and $5.286(10)^{21}$ atoms O/gm Pm_2O_3. The number of atoms lying within the range of any given electron is

$$n = 3.524(10)^{21}R \text{ atoms Pm} \tag{6}$$

$$n = 5.286(10)^{21}R \text{ atoms O.} \tag{7}$$

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Typical cross sections per atom and unit energy are on the order of 10^{-25}. The consequent macroscopic interaction probabilities are on the order of 10^{-4}. This is sufficiently small to justify the use of the approximation indicated in Equation (4). It is, of course, obvious that no energetic interaction is possible at the limit of the range of any electron. The next question to be settled is what fraction of this range can be taken to represent the effective range for the interaction process. A simple computational test can be made. It consists of calculating the bremsstrahlung radiation integral and comparing the result to one of the empirically derived approximations. The approximation derived by Kirkpatrick and Wiedmann (5) was selected for the comparison and establishment of the coefficient of equality. In the checks that were performed using this procedure, essentially a thick-target concept, the bremsstrahlung integral proved to be only 8 to 15 per cent below that predicted by the equation of Kirkpatrick and Wiedmann. It was decided that unity could be the coefficient of equality, since it was believed that the bremsstrahlung integral derived here was in "error" in the right direction.

From the foregoing it may be concluded that the ith element of the jth subspectrum has a total photon flux

$$\emptyset_i = \sigma_i \, nD_j, \tag{8}$$

where D_j = the number of electrons at energy E_j creating the jth spectrum. For a compound, the procedure outlined to this point must be repeated for each element in the compound. For

$$Pm_2O_3, \quad \emptyset \text{ total (I)} = \emptyset_i pm + \emptyset_{io}$$

4.2 COMPUTER PROGRAM AND SUBPROGRAMS

On the following pages a flow diagram for the main program, along with the printer listings of the FORTRAN encoded computer subprograms and main program, are presented. The flow diagram is shown as Figure 4.1. The programs are shown as Tables 4.II- 4.IX. For the most part, the subprograms are in the notation of the references cited. Of course, there is a consistent usage of the order of arguments listed in the "function" statement of the function subprogram and the function "call" of the main program. Although this procedure yields a working computer capability, there will be an apparent ambiguity of notation insofar as there are in the listings several examples of symbols having more than a single

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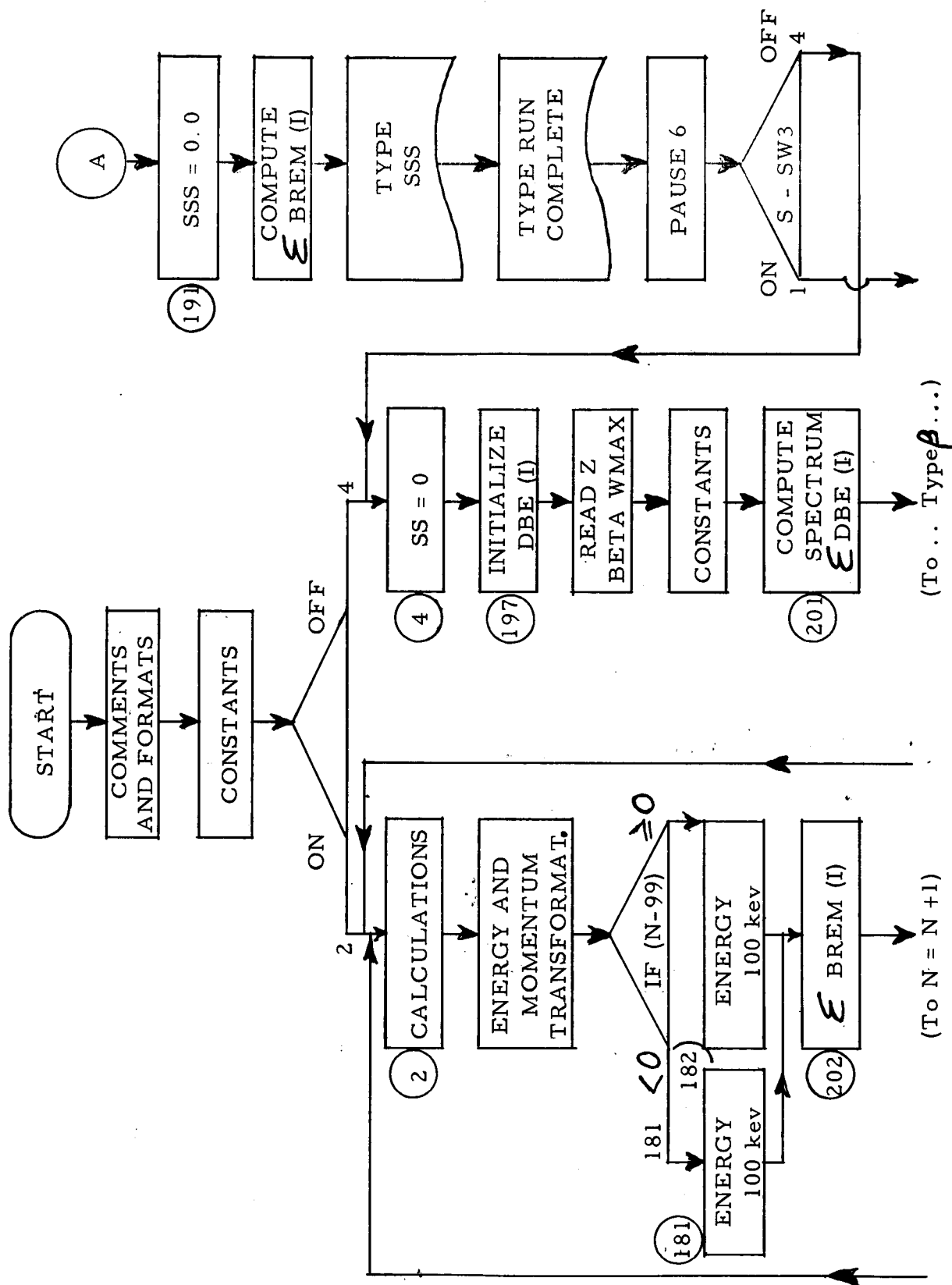
FIGURE 4.1. FLOW DIAGRAM. BETA RAY BREMSSTRAHLUNG

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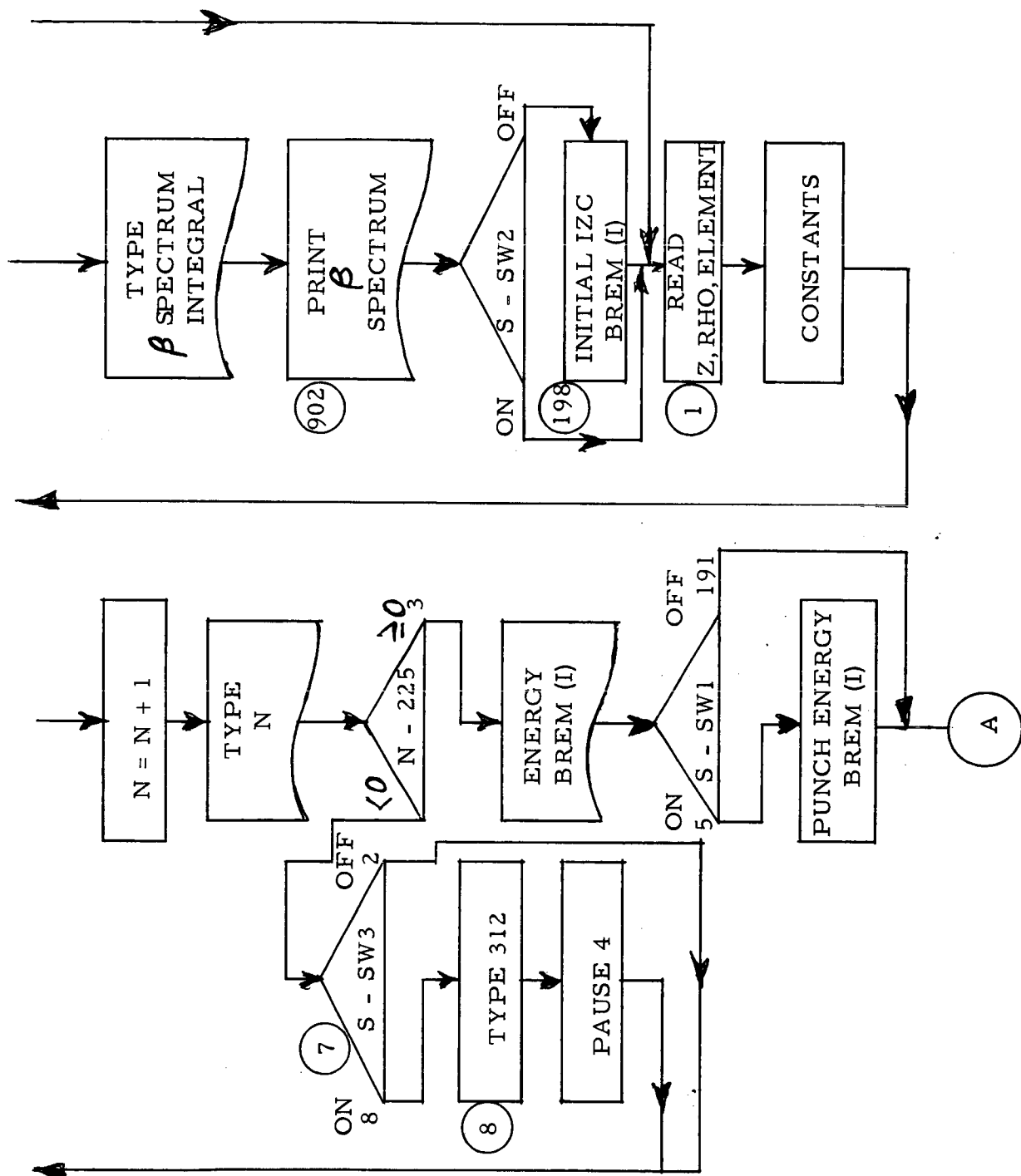
TABLE 4.II

FUNCTION FOR ALLOWED BETA SPECTRUM

```
FUNCTION BETA(F, P, WO, W)
WO = MAXIMUM ENERGY OF TRANSITION
W  = ENERGY OF EMITTED BETA PARTICLE
WOW = WO - W
BETA = F*W*WOW*WOW/P
RETURN
END
```

TABLE 4.III

FERMI FUNCTION - III-A

```
FUNCTION FERMI (ALPHA, PO, PI X 2, ALPHSQ, X, X2)
THIS ROUTINE IS DERIVED FROM H.  HALL,  PHYS. REV. VOL. 79,
NR 4,  PAGE 745 (AUG. 15, 1950) AND MODIFIED BY E. R. RATHBUN
MAY,  1964.
IF (PO) 2, 2, 1

1      POSC = PO*PO
       Y = ALPHA*SQRT(1.0 + POSQ)/PO
       B = ALPHSQ/POSQ + 1.0
       FERMI = PI X 2*PO**X2*EXP(-X2 + Y*2.0 = ATAN(X/Y)) =
           B**(X-5.)*

1      (1.0 + X/(6.0*8))

       RETURN

2      FERMI = 0

RETURN
END
```

TABLE 4. IV

BREMSSTRAHLUNG CROSS SECTIONS - 0.01 TO
0.1 MEV
REV A

```
FUNCTION DS1G01(2 X 2, RO X RC,  DELTA K,  YK, PO, P, ALPHA)
DSIG01 = 2 X 2 *RO X RO*5.3333333*DELTA K*LOG((PO+P)/(PO-P))*
ALPHA/YK*1 PO*PO)
RETURN
END
```

TABLE 4. V

BREMSSTRAHLUNG CROSS SECTIONS - 0.1 TO
2.0 MEV

```
FUNCTION DSIG12(PO, PCSQ, POCUBE, 2 X 2, ROSQ, ALPHA, DELTA
K,  YK, EO, E, P)
REFERENCE - H. W. KOCH AND J. W. MOTZ,  BREMSSTRAHLUNG
CROSS SECTION FORMULAS AND RELATED DATA, REV. MOD. PHYS,
VOL. 31 NR. 4 P 920 (OCT 1959)
EOE = EO*E
POP = PO*P
POPSQ = POP*POP
PSQ - P*P
PCUBE = PSC*P
PO1 = 1.0/PO
YK1 = 1.0/YK
EPS10 = LOG((EO + PO)/(EO - PO))
EPS1 = LOG((E + P)/(E - P))
TL = 2.0*LOG((EOE*POP-1.)*YK1)
TL1 = 1.333333333-2.*EOE*(PSQ+POSQ)/POPSQ + EPS10*E/POCUBE +
1EPS1*EC/PCUBE - EPSI*EPS10/POP
TT2 = 2.666666666*EOE/POP + YK*YK*(EOE*EOE + POPSQ)/(PCUBE*
POCUBE)
TT3 = YK/(2.*POP)*(EPS10*(EOE+PO SQ)/POCUBE - EPS1*(EOE+
PSQ)/1 PCUBE + 2.0*YK*EOE/POPSQ)
DS1012 = 2 X 2*7.93983E-26*ALPHA*P*POI*DELTA K*YKI*(TT1 +
TL*(TT2 + TT3) 1)
RETURN
END
```

TABLE 4. VI

ELWERT FACTOR

```
FUNCTION ELWERT (80, 8, A)
ELWERT = 80*(1.0 - EXP (-6.28318531*A/80))/(8*(1. - EXP
(-6.28318531*A/8 1)))
RETURN
END
```

TABLE 4. VII

FUNCTION AFAC(X, L EMENT)
NR 1

```
FUNCTION AFAC(X,  L EMENT)
GO TO (8, 61),  L EMENT
THIS PROGRAM CONTAINS THE EQUATIONS FOR CORRECTING
THE BREMSSTRAHLUNG DIFFERENTIAL CROSS SECTIONS OF
TARGET OXYGEN,  EQ-8,  AND PROMETHIUM, EQ-61.
8  AFAC = 0.98576088*(1.5635416)**X                    OXYGEN
RETURN
61 AFAC = 1.1336779*(1.6673162)**X                     PH. 1-.5
RETURN
END
```

TABLE 4. VIII

FUNCTION - FLAMMERSFELD EQUATION

```
FUNCTION FLAMMR(EBETA4)
ENERGY OF ELECTRON IS TO BE IN MEV
RESULT IS IN UNITS OF GRAMS PER SQUARE CENTIMETER
FLAMMR = 0.11*(SQRT (1.0 + 22.4*EBETA4*EBETA4) - 1.0)
RETURN
END
```

TABLE 4-IX

BETA-RAY BREMSSTRAHLUNG RADIATION SPECTRUM

*0805CB   BETA-RAY BREMSSTRAHLUNG RADIATION SPECTRUM


```
C
C                                                    PROGRAM PREPARED BY E. R. RATHBUN
C
C                                                             DATE-TIME CODE -
C                                                                 640901170
      FLOAT(I) = I
      ET(X) = 1.95692*X
C     THIS PROGRAM USES THE FOLLOWING SUBPROGRAMS  -  DSIG01 REV. A, DSIG12,
C     ELWERT REV A, AFAC NR1, FERMI III-A, FLAMMR, BETA.
C     THIS PROGRAM HAS TWO RUNS.  THE FIRST COMPUTES THE BETA SPECTRUM OF THE
C     RADIOISOTOPE OF INTEREST.  THE SECOND COMPUTES THE BETA-RAY BREMSSTRAHLUNG
C     SPECTRUM FOR THE ELEMENT OF INTEREST CONSIDERED AS THE TARGET.
C     THE PROGRAM ALSO PROVIDES FOR THE CHAINING IN SEQUENCE THE CALCULATIONS
C     FOR MORE THAN ONE RADIOISOTOPE AND MORE THAN ONE TARGET ELEMENT.
      DIMENSION BREM(250), DBE(250)
      COMMON BREM, DBE, Z, ZXZ, N,AZ, RHO,  L EMENT
   69 FORMAT (     5(I4,1X,E10.3))
  100 FORMAT (5(2X,I4,2X,E11.4,2X))
  101 FORMAT (F10.0, E10.3, I5 )
  102 FORMAT (4X,1HE,6X,5HNR OF 9X,1HE 6X,5HNR OF 9X,1HE 6X,5HNR OF 9X,
     11HE 6X,5HNR OF 9X,1HE 6X,5HNR OF /3X,15HKEV    ELECTRONS 6X,15HKEV
     2  ELECTRONS 6X,15HKEV    ELECTRONS 6X,15HKEV    ELECTRONS 6X,
     3 15HKEV    ELECTRONS  / )
  103 FORMAT (29X,46H BETA-RAY SPECTRUM OF ONE CURIE PROMETHIUM-147  //)
  305 FORMAT (2H   )
  309 FORMAT(1H136X,32HBETA-RAY BREMSSTRAHLUNG SPECTRUM//4X,1HE,6X,5HNR
     1OF9X,1HE6X,5HNR OF9X,1HE6X,5HNR OF9X,1HE6X,5HNR OF9X,1HE,6X,5HNR O
     2F/3X,14HKEV    PHOTONS 7X,14HKEV    PHOTONS 7X,14HKEV    PHOTONS
     3 7X, 14HKEV    PHOTONS 7X,14HKEV    PHOTONS /)
  310 FORMAT (5HSS =  E11.4//)
  311 FORMAT (6HSSS =   E11.4 //)
  312 FORMAT (38H LOAD  DUMP COMMON, THEN ENTER  34950.      )
  313 FORMAT (38HRUN COMPLETE, START 1401, PRESS START.  )
  314 FORMAT (59HTO PRESERVE EXISTING BREMSSTRAHLUNG SPECTRUM, SET SW2 O
     1N.  )
  315 FORMAT (4HN =  I5)
      PII  = 3.14159265358979323846264338327950288419716939937510582
      PIX2 = 2.0*PII
      ALPHA = 7.297203E-03
      RO    = 2.81777E-13
      ROXRO = RO*RO
      D = ET(0.001)
      W = 1.0
      YKMIN = ET(0.01) - D
C     TO BEGIN PROGRAM, SET SW2 OFF.
C     SET SW2 ON IF BETA-RAY SPECTRUM HAS BEEN LOADED INTO COMMON STORAGE.
      IF (SENSE SWITCH 2) 2,4
C     SET UP BETA RAY SPECTRUM
    4 SS = 0.0
      DO 197 I = 1,250
  197 DBE(I) = 0.0
      READ 101, ZBETA, WMAX
      WWMAX = ET(WMAX) + 1.0
```

TABLE 4-IX (contd)

BETA-RAY BREMSSTRAHLUNG RADIATION SPECTRUM

```
      A = ZBETA*ALPHA
      AA = A*A
      X = SQRT(1.0 - AA)
      X2 = X + X
      DO 201 I=1,224
      W = W + D
      PW = SQRT(W*W - 1.0)
      F = FERMI(A,PW,PIX2,AA,X,X2)
      DBE(I) =3.239E+11*BETA(F,PW,WWMAX,W)*D
  201 SS = SS + DBE(I)
      TYPE 310, SS
      TYPE 313
      PAUSE 1
      PRINT 103
      PRINT 102
      I = 0
      DO 901  J = 1,5
      DO 902  JJ = 1,10
      I = I + 1
      N1 = I
      N2 = I + 50
      N3 = I + 100
      N4 = I + 150
      N5 = I + 200
  902 PRINT 100, N1,DBE(I),N2,DBE(N2),N3,DBE(N3),N4,DBE(N4),N5,DBE(N5)
  901 PRINT 305
      PAUSE 2
C     SET UP BREMSSTRAHLUNG SPECTRAL ELEMENTS.
      TYPE 314
      PAUSE 3
      IF (SENSE SWITCH 2) 1,198
  198 DO 199 I=1,250
  199 BREM(I) = 0.0
    1 READ 101, Z, RHO,    L EMENT
      AZ = ALPHA*Z
      ZXZ = Z*Z
      N = 10
    2 YK = YKMIN
      E4 = FLOAT(N + 1)*0.001
      DD = DBE(N + 1)
C     RHO = ATOMIC NUMBER DENSITY OF GIVEN ELEMENT IN COMPOUND.   UNITS OF
C     RHO ARE   NUMBER OF ATOMS OF TARGET ELEMENT PER GRAM OF COMPOUND.
      RANGE = FLAMMR(E4)*RHO
      TO = ET(E4)
      AF =  AFAC(TO,  L EMENT)
      EO = TO + 1.0
      POSQ = TO*(TO + 2.0)
      PO = SQRT(POSQ)
      POCUBE = POSQ*PO
      BO = PO/EO
      DO202 I = 10,N
      YK = YK + D
      E = EO - YK
      T = E - 1.0
      P = SQRT(T*(T + 2.0))
      B = P/E
```

TABLE 4-IX (contd)

BETA-RAY BREMSSTRAHLUNG RADIATION SPECTRUM

```
      ELW = ELWERT(BO,B,AZ)
      LF (N - 99) 181,182,182
  181 DSIG =    DSIGO1(ZXZ,ROXRO, D       ,YK,PO,P,ALPHA )*ELW
      GO TO 202
  182 DSIG =    DSIG12(PO,POSQ,POCUBE,ZXZ,ROSQ,ALPHA,D       , YK,EO,E,P)
    1 *ELW*AF
  202 BREM(I) = BREM(I) + DSIG*RANGE*DD
      N = N + 1
      TYPE 315, N
      LF (N - 225) 7,3,3
C     SET SW3 ON TO HALT AND LOAD PROGRAM    DUMP COMMON.
    7 LF (SENSE SWITCH 3) 8,2
    8 TYPE 312
      PAUSE 4
C     TO CONTINUE, PRESS START, SW3 OFF.
      GO TO 2
    3 CONTINUE
      TYPE 313
      PAUSE 5
      PRINT 309
      L = 0
      DO 71 J = 1,5
      DO 70  JJ = 1,10
      I = I + 1
      N1 = I
      N2 = I + 50
      N3 = I + 100
      N4 = I + 150
      N5 = I + 200
   70 PRINT100, N1,BREM(I),N2,BREM(N2),N3,BREM(N3),N4,BREM(N4),N5,BREM(N
    1 5)
   71 PRINT 305
C     SENSE SWITCH ON FOR PUNCHED OUTPUT   SW1
      LF (SENSE SWITCH 1) 5,1
    5 DO 68  I = 1,50
      N1 = I
      N2 = I + 50
      N3 = I + 100
      N4 = I + 150
      N5 = I + 200
   68 PUNCH 69, N1,BREM(I),N2,BREM(N2),N3,BREM(N3),N4,BREM(N4),N5,BREM(N
    1 5)
      SSS = 0.0
      DO 65 I = 1,250
   65 SSS = SSS + BREM(L)
      TYPE 311,  SSS
      TYPE 313
      PAUSE 6
C     SW3 ON    READ NEW Z, RHO,  L EMENT
C     SW3 OFF   READ NEW ZBETA AND WMAX
      LF (SENSE SWITCH 3) 1,4
      END

12110     19569200 01
12120     31415926 01
12130     20000000 01
```

meaning. This flexibility, inherent in FORTRAN coding, eliminated the need for organizing a single symbol system and thus saved programming time.

The main program as it is listed now is presently only able to compute the beta ray bremsstrahlung spectrum function of promethium compounds. The present capability is further restricted to the compound Pm_2O_3 because the function subprogram AFAC contains only those equations for promethium and oxygen. However, AFAC can be enlarged at any time, and the main program can be generalized so that it may be used in the calculation of the bremsstrahlung properties of other beta ray emitters. Furthermore, it also has become obvious that the beta ray spectrum of isotopes possessing more intricate decay schemes may be computed with one or more separate programs whose purpose is to provide spectral data on one or more contaminants that may be present in the desired isotope. In this manner, very complicated beta ray spectrum functions may be used as data for beta ray bremsstrahlung spectrum function calculations.

As the main program is now arranged, three data cards are used in the course of the complete calculation. The first card gives the atomic number of the daughter nucleus and the maximum energy of the beta ray transition, 0.225 Mev for Pm-147. This provides the necessary data for the beta ray spectrum function to be computed. The second card read by the programmed computer carries the atomic number of the target element (Pm), the number of atoms of the target element per gram of compound, and an identifying number for the correction term generated by the subprogram AFAC. A third card, identical in form and nature of data to the second card, was also used in the computational test executed as a part of this computer program development effort. The third card carried data pertaining to the target element oxygen in the compound Pm_2O_3.

4.3 RESULTS

The results of the computation discussed in 4.1 and 4.2 were obtained in two steps. The first step consisted of calculating the beta ray spectrum function for Pm-147 by means of Equation (2). The second step consisted of using the beta ray spectrum function as input data in the much more lengthy calculation of the beta ray bremsstrahlung function. In Table 4.X the beta ray spectrum function is tabulated in units of electrons/sec kev curie. A graph of this function is also presented in Fig. 4.2. The results of the computation to obtain the bremsstrahlung function are tabulated in units of photons/sec kev curie, Table 4.XI, and are graphically presented in Fig. 4.3.

TABLE 4. X

BETA-RAY SPECTRUM OF ONE CURIE PROMETHIUM-147

E KEV	NR OF ELECTRONS	E KEV	NR OF ELECTRONS	E KEV	NR OF ELECTRONS	E KEV	NR OF ELECTRONS	E KEV	NR OF ELECTRONS
1	4.1420E+08	51	2.9057E+08	101	1.7032E+08	151	6.9495E+07	201	8.3086E+06
2	4.1183E+08	52	2.8808E+08	102	1.6805E+08	152	6.7808E+07	202	7.6497E+06
3	4.0945E+08	53	2.8559E+08	103	1.6579E+08	153	6.6137E+07	203	7.0163E+06
4	4.0706E+08	54	2.8311E+08	104	1.6354E+08	154	6.4482E+07	204	6.4089E+06
5	4.0466E+08	55	2.8063E+08	105	1.6130E+08	155	6.2843E+07	205	5.8275E+06
6	4.0225E+08	56	2.7815E+08	106	1.5906E+08	156	6.1221E+07	206	5.2723E+06
7	3.9983E+08	57	2.7567E+08	107	1.5684E+08	157	5.9616E+07	207	4.7437E+06
8	3.9741E+08	58	2.7319E+08	108	1.5462E+08	158	5.8027E+07	208	4.2417E+06
9	3.9498E+08	59	2.7071E+08	109	1.5241E+08	159	5.6455E+07	209	3.7667E+06
10	3.9254E+08	60	2.6824E+08	110	1.5021E+08	160	5.4901E+07	210	3.3187E+06
11	3.9010E+08	61	2.6577E+08	111	1.4802E+08	161	5.3363E+07	211	2.8981E+06
12	3.8765E+08	62	2.6331E+08	112	1.4583E+08	162	5.1844E+07	212	2.5051E+06
13	3.8519E+08	63	2.6084E+08	113	1.4366E+08	163	5.0342E+07	213	2.1398E+06
14	3.8273E+08	64	2.5838E+08	114	1.4150E+08	164	4.8858E+07	214	1.8025E+06
15	3.8027E+08	65	2.5592E+08	115	1.3934E+08	165	4.7392E+07	215	1.4933E+06
16	3.7780E+08	66	2.5346E+08	116	1.3720E+08	166	4.5944E+07	216	1.2126E+06
17	3.7533E+08	67	2.5101E+08	117	1.3506E+08	167	4.4515E+07	217	9.6053E+05
18	3.7286E+08	68	2.4856E+08	118	1.3294E+08	168	4.3105E+07	218	7.3725E+05
19	3.7038E+08	69	2.4611E+08	119	1.3082E+08	169	4.1713E+07	219	5.4303E+05
20	3.6790E+08	70	2.4367E+08	120	1.2872E+08	170	4.0341E+07	220	3.7807E+05
21	3.6542E+08	71	2.4123E+08	121	1.2662E+08	171	3.8988E+07	221	2.4261E+05
22	3.6294E+08	72	2.3880E+08	122	1.2454E+08	172	3.7654E+07	222	1.3685E+05
23	3.6045E+08	73	2.3636E+08	123	1.2247E+08	173	3.6340E+07	223	6.1016E+04
24	3.5796E+08	74	2.3394E+08	124	1.2041E+08	174	3.5045E+07	224	1.5326E+04
25	3.5547E+08	75	2.3151E+08	125	1.1836E+08	175	3.3771E+07	225	0.0000E-99
26	3.5298E+08	76	2.2909E+08	126	1.1632E+08	176	3.2517E+07	226	0.0000E-99
27	3.5049E+08	77	2.2668E+08	127	1.1429E+08	177	3.1283E+07	227	0.0000E-99
28	3.4799E+08	78	2.2427E+08	128	1.1227E+08	178	3.0070E+07	228	0.0000E-99
29	3.4550E+08	79	2.2186E+08	129	1.1027E+08	179	2.8877E+07	229	0.0000E-99
30	3.4300E+08	80	2.1946E+08	130	1.0828E+08	180	2.7706E+07	230	0.0000E-99
31	3.4050E+08	81	2.1706E+08	131	1.0630E+08	181	2.6556E+07	231	0.0000E-99
32	3.3801E+08	82	2.1467E+08	132	1.0433E+08	182	2.5427E+07	232	0.0000E-99
33	3.3551E+08	83	2.1228E+08	133	1.0237E+08	183	2.4320E+07	233	0.0000E-99
34	3.3301E+08	84	2.0990E+08	134	1.0043E+08	184	2.3234E+07	234	0.0000E-99
35	3.3051E+08	85	2.0752E+08	135	9.8503E+07	185	2.2171E+07	235	0.0000E-99
36	3.2801E+08	86	2.0515E+08	136	9.6586E+07	186	2.1130E+07	236	0.0000E-99
37	3.2551E+08	87	2.0278E+08	137	9.4682E+07	187	2.0111E+07	237	0.0000E-99
38	3.2301E+08	88	2.0042E+08	138	9.2791E+07	188	1.9114E+07	238	0.0000E-99
39	3.2051E+08	89	1.9807E+08	139	9.0913E+07	189	1.8141E+07	239	0.0000E-99
40	3.1801E+08	90	1.9572E+08	140	8.9049E+07	190	1.7190E+07	240	0.0000E-99
41	3.1551E+08	91	1.9338E+08	141	8.7199E+07	191	1.6263E+07	241	0.0000E-99
42	3.1302E+08	92	1.9104E+08	142	8.5363E+07	192	1.5359E+07	242	0.0000E-99
43	3.1052E+08	93	1.8871E+08	143	8.3541E+07	193	1.4478E+07	243	0.0000E-99
44	3.0802E+08	94	1.8639E+08	144	8.1733E+07	194	1.3622E+07	244	0.0000E-99
45	3.0552E+08	95	1.8407E+08	145	7.9940E+07	195	1.2789E+07	245	0.0000E-99
46	3.0303E+08	96	1.8176E+08	146	7.8162E+07	196	1.1980E+07	246	0.0000E-99
47	3.0053E+08	97	1.7946E+08	147	7.6398E+07	197	1.1196E+07	247	0.0000E-99
48	2.9804E+08	98	1.7716E+08	148	7.4649E+07	198	1.0437E+07	248	0.0000E-99
49	2.9555E+08	99	1.7487E+08	149	7.2916E+07	199	9.7027E+06	249	0.0000E-99
50	2.9306E+08	100	1.7259E+08	150	7.1197E+07	200	8.9930E+06	250	0.0000E-99

FIGURE 4.2 BETA RAY SPECTRUM Pm¹⁴⁷
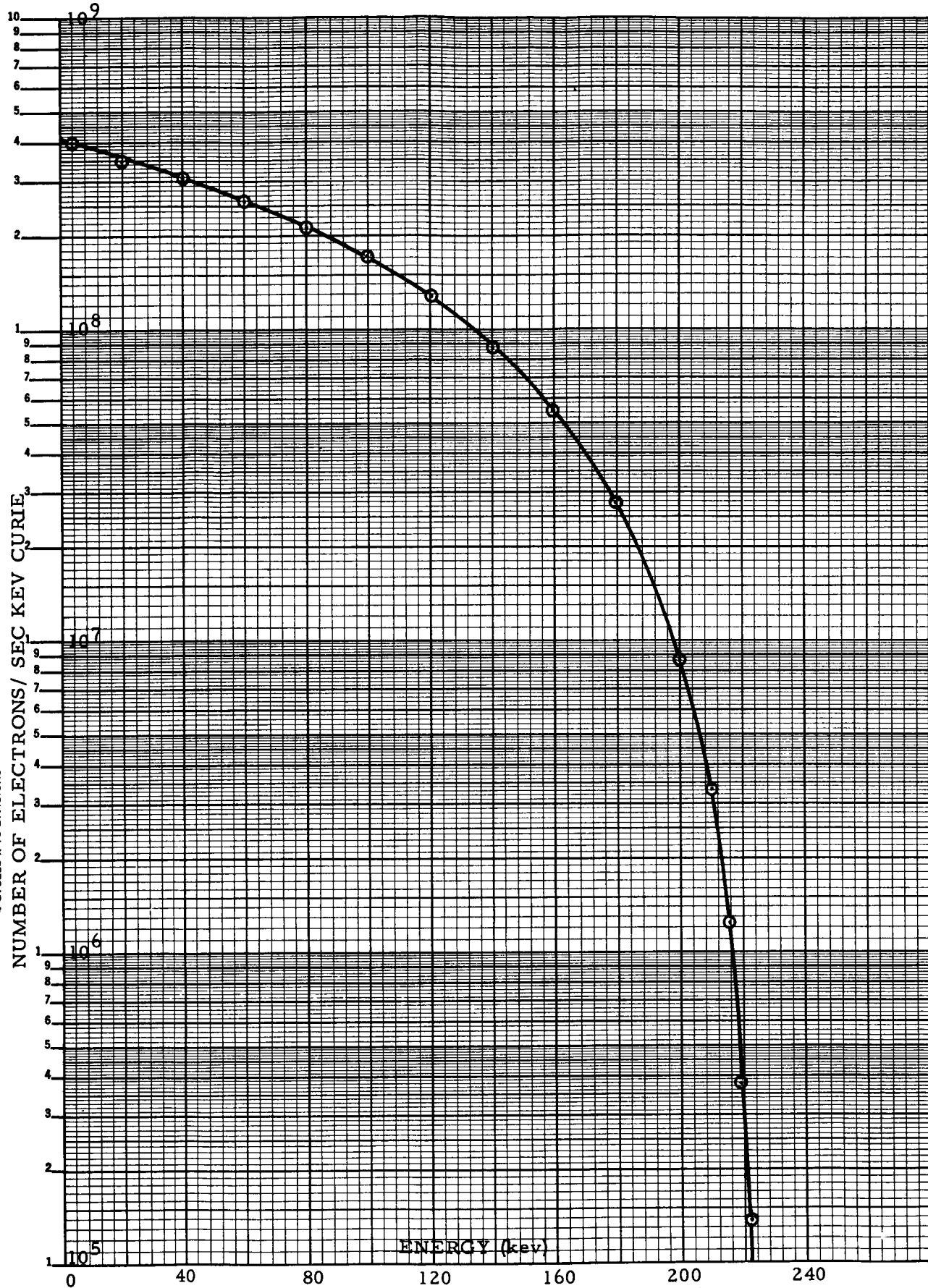
FIGURE 4.2 BETA RAY SPECTRUM Pm^{147}

TABLE 4.XI

BETA-RAY BREMSSTRAHLUNG SPECTRUM

| E KEV	NR OF PHOTONS	E KEV	NR OF PHOTONS	E KEV	NR OF PHOTONS	E KEV	NR OF PHOTONS	E KEV	NR OF PHOTONS
1	0.0000E-99	51	0.0000E-99	101	0.0000E-99	151	0.0000E-99	201	0.0000E-99
2	0.0000E-99	52	0.0000E-99	102	0.0000E-99	152	0.0000E-99	202	0.000CE-99
3	0.0000E-99	53	0.0000E-99	103	0.0000E-99	153	0.0000E-99	203	0.0000E-99
4	0.0C00E-99	54	0.0000E-99	104	0.0000E-99	154	0.0000E-99	204	0.0000E-99
5	0.0000E-99	55	0.0000E-99	105	0.0000E-99	155	0.0000E-99	205	0.0000E-99
6	0.0000E-99	56	0.0000E-99	106	0.0000E-99	156	0.0000E-99	206	0.0000E-99
7	0.0000E-99	57	0.0000E-99	107	0.0000E-99	157	0.0000E-99	207	0.0000E-99
8	0.0000E-99	58	0.0000E-99	108	0.0000E-99	158	0.0000E-99	208	0.0000E-99
9	0.0000E-99	59	0.0000E-99	109	0.0000E-99	159	0.0000E-99	209	0.0000E-99
10	7.3483E+05	60	0.0000E-99	110	0.0000E-99	160	0.0000E-99	210	0.0000E-99
11	6.3888E+05	61	0.0000E-99	111	0.0000E-99	161	0.0000E-99	211	0.0000E-99
12	5.6020E+05	62	0.0000E-99	112	0.0000E-99	162	0.0000E-99	212	0.0000E-99
13	4.9454E+05	63	0.0000E-99	113	0.0000E-99	163	0.0000E-99	213	0.0000E-99
14	4.3891E+05	64	0.0000E-99	114	0.0000E-99	164	0.0000E-99	214	0.0000E-99
15	3.9117E+05	65	0.0000E-99	115	0.0000E-99	165	0.0000E-99	215	0.0000E-99
16	3.4972E+05	66	0.0000E-99	116	0.0000E-99	166	0.0000E-99	216	0.0000E-99
17	3.1339E+05	67	0.0000E-99	117	0.0000E-99	167	0.0000E-99	217	0.0000E-99
18	2.8126E+05	68	0.0000E-99	118	0.0000E-99	168	0.0000E-99	218	0.0000E-99
19	2.5262E+05	69	0.0000E-99	119	0.0000E-99	169	0.0000E-99	219	0.0000E-99
20	2.2691E+05	70	0.0000E-99	120	0.0000E-99	170	0.0000E-99	220	0.0000E-99
21	2.0368E+05	71	0.0000E-99	121	0.0000E-99	171	0.0000E-99	221	0.0000E-99
22	1.8258E+05	72	0.0000E-99	122	0.0000E-99	172	0.0000E-99	222	0.0000E-99
23	1.6332E+05	73	0.0000E-99	123	0.0000E-99	173	0.0000E-99	223	0.0000E-99
24	1.4564E+05	74	0.0000E-99	124	0.0000E-99	174	0.0000E-99	224	0.0000E-99
25	1.2935E+05	75	0.0000E-99	125	0.0000E-99	175	0.0000E-99	225	0.0000E-99
26	1.1428E+05	76	0.0000E-99	126	0.0000E-99	176	0.0000E-99	226	0.0000E-99
27	1.0029E+05	77	0.0000E-99	127	0.0000E-99	177	0.0000E-99	227	0.0000E-99
28	8.7267E+04	78	0.0000E-99	128	0.0000E-99	178	0.0000E-99	228	0.0000E-99
29	7.5090E+04	79	0.0000E-99	129	0.0000E-99	179	0.0000E-99	229	0.0000E-99
30	6.3681E+04	80	0.0000E-99	130	0.0000E-99	180	0.0000E-99	230	0.0000E-99
31	5.2963E+04	81	0.0000E-99	131	0.0000E-99	181	0.0000E-99	231	0.0000E-99
32	4.2870E+04	82	0.0000E-99	132	0.0000E-99	182	0.0000E-99	232	0.0000E-99
33	3.3344E+04	83	0.0000E-99	133	0.0000E-99	183	0.0000E-99	233	0.0000E-99
34	2.4336E+04	84	0.0000E-99	134	0.0000E-99	184	0.0000E-99	234	0.0000E-99
35	1.5801E+04	85	0.0000E-99	135	0.0000E-99	185	0.0000E-99	235	0.0000E-99
36	7.7011E+03	86	0.0000E-99	136	0.0000E-99	186	0.0000E-99	236	0.0000E-99
37	0.0000E-99	87	0.0000E-99	137	0.0000E-99	187	0.0000E-99	237	0.0000E-99
38	0.0000E-99	88	0.0000E-99	138	0.0000E-99	188	0.0000E-99	238	0.0000E-99
39	0.0000E-99	89	0.0000E-99	139	0.0000E-99	189	0.0000E-99	239	0.0000E-99
40	0.0000E-99	90	0.0000E-99	140	0.0000E-99	190	0.0000E-99	240	0.0000E-99
41	0.0000E-99	91	0.0000E-99	141	0.0000E-99	191	0.0000E-99	241	0.0000E-99
42	0.0000E-99	92	0.0000E-99	142	0.0000E-99	192	0.0000E-99	242	0.0000E-99
43	0.0000E-99	93	0.0000E-99	143	0.0000E-99	193	0.0000E-99	243	0.0000E-99
44	0.0000E-99	94	0.0000E-99	144	0.0000E-99	194	0.0000E-99	244	0.0000E-99
45	0.0000E-99	95	0.0000E-99	145	0.0000E-99	195	0.0000E-99	245	0.0000E-99
46	0.0000E-99	96	0.0000E-99	146	0.0000E-99	196	0.0000E-99	246	0.0000E-99
47	0.0000E-99	97	0.0000E-99	147	0.0000E-99	197	0.0000E-99	247	0.0000E-99
48	0.0000E-99	98	0.0000E-99	148	0.0000E-99	198	0.0000E-99	248	0.0000E-99
49	0.0000E-99	99	0.0000E-99	149	0.0000E-99	199	0.0000E-99	249	0.0000E-99
50	0.0000E-99	100	0.0000E-99	150	0.0000E-99	200	0.0000E-99	250	0.0000E-99
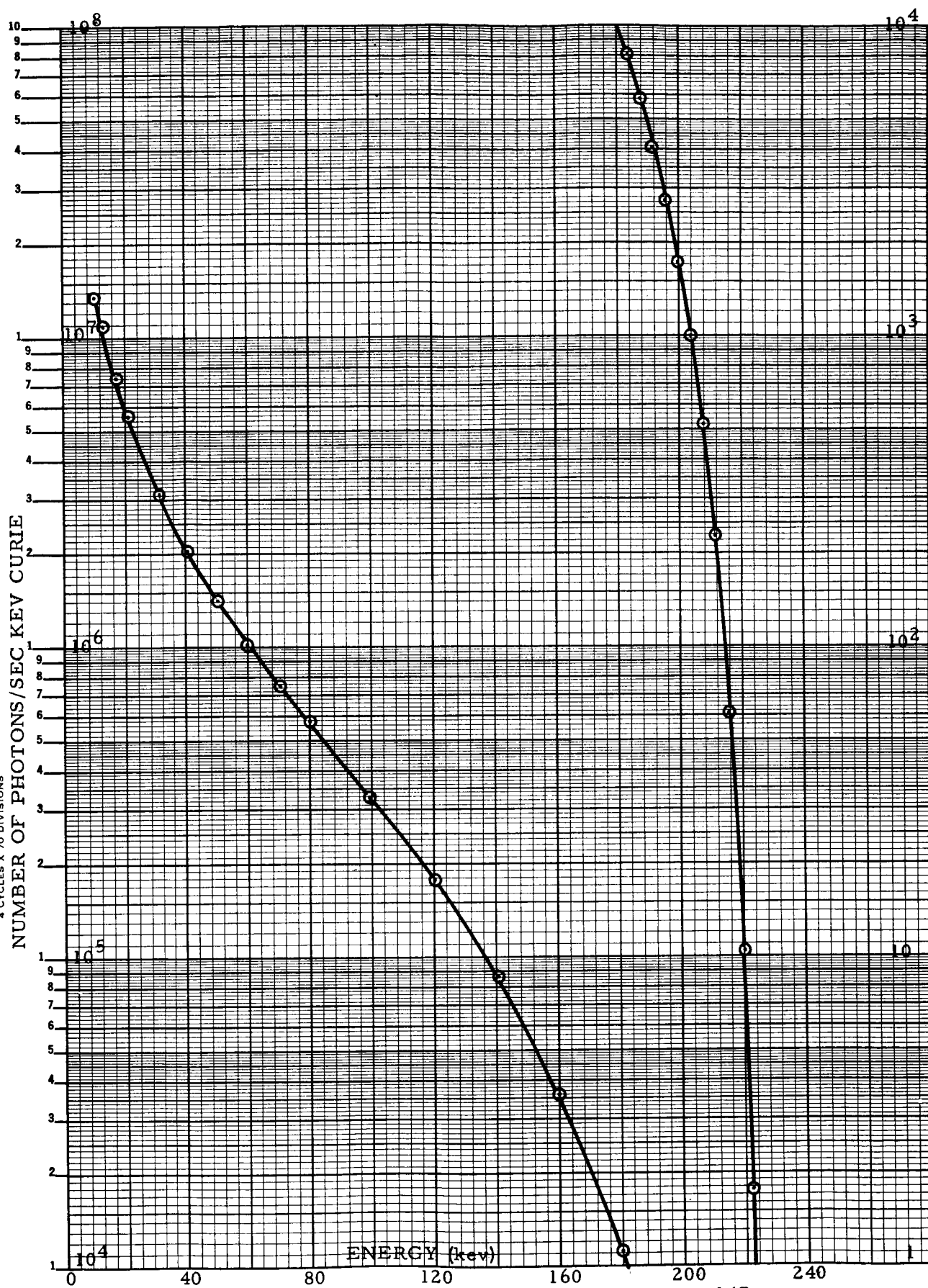
FIGURE 4.3 BREMSSTRAHLUNG SPECTRUM- $^{147}Pm_2O_3$

Integration of the bremsstrahlung function presented here yields $2.19(10)^8$ photons/sec curie, suggesting a beta particle to photon conversion efficiency of 0.59 per cent.

Another interesting result is the beta particle to photon conversion efficiency for oxygen. This quantity has been found to be 0.012 per cent, 2.07 per cent of the promethium contribution. The accuracy claimed for the equations used in the computation is not better than 5 per cent or 20 per cent, depending upon the range in which they are used. The conclusion to be drawn from this is that it is probably not worth while to calculate the contribution of the lighter elements accurately. Approximate corrections to the effects of a heavy element are probably sufficient for elements whose atomic numbers are less than one-fourth the atomic number of the heavy element. Further study of the conditions necessary for making approximations of this type, and for cases where there are more than two elements in the compound, is recommended. Of course, for light elements whose chemical abundances are larger than an approximate one to one ratio, the computing of the total bremsstrahlung function from the sum of the accurately computed parts may be necessary.

It is also to be seen in Figure 4.2 that the bremsstrahlung function rises monotonically as zero is approached. However, because of the internal self-absorption process in an isotopic source having appreciable mass, it is believed that for an experiment with a real source, a maximum radiation intensity will be seen. This is probable because at some point on the curve, absorption probabilities will greatly exceed the bremsstrahlung probabilities.

The results of a computer computation for a specific configuration of a radioisotope fuel element should show this maximum intensity somewhere below the end point. (This calculation has not been performed.) In this operation the bremsstrahlung computation presented would provide the data for this next step.

Work on Pm-147 in the form of Pm_2O_3 has been completed. From time to time in the course of the study, other references were found to have data useful to program or that could be directly compared with the results of this study. A summary of the work of five investigators are tabulated for comparison with the results of this study in Table 4.XII.

TABLE 4. XII

PROPERTIES OF Pm-147

	Ref. 6	Ref. 7	Ref. 8	Ref. 9	Ref. 10	This Study
Specific power pure Pm-147, w/gm	0.33	0.362	0.41.(b)			0.335(a)
Half-life, years	2.7	2.67	2.67	2.5		2.67
Purity of compound Pm_2O_3, %	95.		95.			95.
Specific power 95% Pm_2O_3, w/g	0.27		0.324(b)			0.274(a)
Density, g/cm^3	6.6	6.72	6.6			6.6
Specific power 95% Pm_2O_3, w/K curie	0.361	0.397	*0.41			0.368(a)
Power density 95% Pm_2O_3, w/cm^3	1.8	2.0	2.03			1.805(a)
Average energy of electrons, Mev.		0.067		0.073	0.063	0.062(a)
Maximum energy electrons, Mev	0.225	0.230	0.225		0.225	0.225
Specific activity pure Pm-147, c/g	914.	912.	*1000.	*980.		911.(a)
Specific activity pure Pm-147, c/w	2770.	2520.	2440.			2720.(a)
Specific activity pure Pm_2O_3, c/g						783.(a)
Specific activity 95% Pm_2O_3, c/g				(*830. (390. (600.		744.(a)

*Radioactive contaminants and impurities are suggested as the source of difficulty.

(a) Values derived from theoretical considerations in this study program.

(b) The arithmetic seems to be inconsistent when compared with the theoretical values derived in this study.

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4.5   THE BREMSSTRAHLUNG COMPUTER PROGRAM BIBLIOGRAPHY

During the development of the computer program many bremsstrahlung references were investigated. Some of these references were used in the development of the foregoing computer program. As the subject program concluded it was felt that perhaps even those references not used directly in the program might be of some use to various interested persons reading this report. For this reason these references are cited.

The references, with one or two exceptions, were all taken from the Nuclear Science Abstracts, 1948 to 15 August 1964. This literature search was limited to those references that were thought to be most pertinent to the subject program and so should not be construed to be an all encompassing search. With this thought in mind the bremsstrahlung bibliography is presented as follows:

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5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 EXTENSION OF THE PRESENT BIBLIOGRAPHY.

As was stated in the introduction, the annotated bibliographies contained in this report were taken from the unclassified literature. As can be seen, there seems to be an abundance of information on the isotopes Cs-134, Cs-137, and Po-210, and within reason, for Pm-147. However, it would seem that there should be more information available on Sr-90, Pu-238, and Cm-242, 244. (Especially for the period 1960-64.)

In the proposal (7P4445) that the Tech-Center Division of Cook Electric Company submitted to the Advanced Power Section of NASA, GSFC, it stated that the literature search would be made to ascertain the complete known nuclear characteristics of the isotopes under study in their pure and contaminated forms and in their usable fuel forms. For the most part there seems to be adequate information in the unclassified literature describing the nuclear characteristics of the isotopes in their pure and simple compound forms. In fact, the aim of most of the investigators was to obtain the isotopes in as pure a form as possible. As a direct result of this, very little information was accumulated on the radiation characteristics of the isotopes in heavily contaminated, or complex, compound form. This was especially true for the isotopes Pm-147, Pu-238, Cm-242, and Cm-244. It is for this reason that the following recommendation is made.

A search of the classified literature for the period 1958 to the present should be conducted to gain more detailed information on the radiation characteristics of the eight isotopes reviewed with special emphasis on Pm-147, Pu-238, Cm-242, and Cm-244. It is expected that the bulk of the literature search would be made on reports emanating from the following facilities:

1.	The Martin Company	Sr-90
2.	Oak Ridge National Laboratories	Cm-242, Cm-244
3.	Mound Laboratories	Pu-238 (Po-210)
4.	Lawrence Radiation Laboratories (Berkeley and Livermore, California)	Cm-242, Cm-244, Pu-238
5.	Hanford Atomic Laboratories	Pm-147

In addition to a search of the classified reports published by these facilities, it is expected that personal visits would be made to most of them. (Several personal contacts have been made during

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the course of the present program that will prove to be quite valuable in a follow-on program.)

5.2   In addition to the isotopes studied in the present effort there are three (and possibly two more) isotopes whose nuclear characteristics deserve an up-to-date investigation.   These are:

1.   Cerium-144
2.   Actinium-227
3.   Thorium-228
4.   Californium-250 (possible)
5.   Californium-252 (possible)

A cursory examination has been made of all five of these isotopes.   A table of the nuclear characteristics of these isotopes as listed in the Review of Modern Physics 1958 is presented as follows:

	Isotope	Half Life	Principal Radiations	Energy (Mev)	% Abund.
1.	Ce-144	285 days	Beta	0.309	75
				0.175	25
			Gamma	0.1452 (hardest)	
2.	Ac-227	21.6 years	Beta	0.046	99
			Alpha	5.03	
			Gamma	0.037 (weak)	
3.	Th-228	1.91 years	Alpha	5.421	71
				5.338	28
			Gamma	0.0845	
				0.132	
				0.167	
				0.214	
4.	Cf-250	10.9 years	Alpha	6.024	83
				5.980	17
			Gamma	0.0429	
5.	Cf-252	2.2 years	Sp. Fission		3
			Alpha		97
			Alpha	6.112	88
				6.069	15
			Gamma	0.0434	

It is recognized that items 4 and 5 are available at present only in microcurie quantities. However, their nuclear characteristics make them attractive for consideration.

It is further recommended, therefore, that the unclassified and classified literature be investigated for the purpose of updating the information available on items 1, 2, and 3 and for investigating in depth the characteristics of items 4 and 5. Two reports would be generated from this search, one classified and one unclassified.

5.3   Recommendations for Future Work in the Study of Beta Ray Bremsstrahlung Radiation. In this program, as in any other, where the technology is still undergoing development, the choice of future work is largely one of outlining tasks that are in logical order, without omissions, and which lead to pre-selected goals as the work progresses. With this philosophy in mind, it appears appropriate to set forth the following course of action:

1.   Complete the checking of the beta ray bremsstrahlung function for Pm_2O_3 and summarize the results.

2.   Extend the work on the Fermi function so that one or more of the "forbidden" transitions may be handled by a computer subprogram.

3.   Separate the function of computing the beta ray spectrum function from the present main program and provide for the components of the spectra of contaminants and compound decay schemes. Generalize energy range capability.

4.   Revise and generalize the present main program so that it will function in sequence with the beta ray spectrum function programs suggested above without restriction as to isotope or energy range.

5.   Extend computer program library to include capability of determining the effect of self absorption on a few selected forms of isotopic heat source elements.

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6.   Investigate the nature and degree of importance
        of "characteristic" X-rays relative to
        bremsstrahlung radiation.

7.   Review and analyze two other known programs
        designed to perform beta ray bremsstrahlung
        radiation function calculations.